uc3m | Universidad Carlos III de Madrid

University Degree in Aerospace Engineering

2016/2017

Bachelor Tesis

Trajectory Optimization for Asteroid Mining

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16/10/2017

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Abstract

Near Earth Asteroids might become key in the future development of mining and space industry. Their exploitation would give access to a huge amount of minerals and metals that could be used to create an "in-space manufacturing industry" and that could be used also to support deep space missions and stations through in situ resource utilization. However, a deep knowledge of minearologic composition and dynamic distribution of these bodies would be required in order to attain these achievements.

This work tries to shed light to the matters of what NEAs should be considered in a mining project, what orbital parameters are going to influenced energetic cost required to reach them and how transfer trajectories could be optimized. A total of twelves NEAs have been analysed through four different methods, employing an straightforward resolution of Lambert's Problem and genetic algorithms. Optimization of the previous trajectories have been studied through a Patched Conics Method, solving it also making use of a direct approach and with NSGA-II.

Agradecimientos

A Manuel, porque sin su conocimiento y su guía habría resultado imposible sacar adelante este trabajo.

A Miguel, Elena, Elenita y Celia, porque me han demostrado que siempre puedo esperar lo mejor de ellos, su cariño.

A mis padres, a quienes debo este trabajo, mis estudios, mis valores y mi vida entera. Porque en ningún momento han dejado de apoyarme, al igual que no han dejado de mostrarme los caminos que se han abierto ante mí, dejándome elegir entre ellos.

A mis hermanos. A Javier, mi referente y modelo, quien me sigue transmitiendo la belleza que se esconde tras la ciencia y la música. A Miguel, quien, por el contrario, me enseña que no debemos dejar de aprender de quienes vienen detrás de nosotros, pues vienen con fuerza suficiente para sobrepasarnos a todos.

A Laura, por estar ahí cada segundo de este trabajo y de los últimos años, aguantando mis nervios e inseguridades. Ayudándome también a superarlos cuando más lo necesitaba y a dejarlos de lado y disfrutar de los momentos que lo merecen. Haces que vea lo mejor de mí y que consiga aprender de lo peor.

Chapter 1

Introduction

> We only need to lift up our eyes and look at the wealth of energy and materials that surrounds us in space
>
> John S. Lewis

1.1 Mining and metal industry socio-economic context

Minerals, metals and materials have always been a primordial key in society development and growth. Each step towards extraction or production enhancement has led to demographic and economic growth and has change society. The very firsts materials that has been used by humans were the ones that were easier to find and work, like stone, wood, skin, leather and clay, for example. The use of these materials through thousands of year and the learning that came from it led to the first tools made using this materials, and the same process repeated again but whit these new tools led again to new tools and materials. [2]

Some of the first objects that has been found are dated around the ninth-seventh millennia BC [3], these were tools like pins, awls and ornaments. These objects were not melted, the raw metal used to made them was extracted directly from natural outcrops and cold worked and hammered into small beads. As said before, these firts uses of the copper were before Copper Age had begun, still in the Neolithic Age. The articles that could be worked out of the raw copper were highly limited by the size of the unmelted nuggets, found as native crystals which had metallic form and microstructure. These crystals were later heated below copper melting temperature and then annealed. There are some examples of prehistoric blades forged by cold working with sizes up to twenty centimeters, but this was not the rule. Thousands of year had to pass until tools, weapons and bigger instruments than these jewels found in Anatolia started to be manufactured in the Tigris and Euphrates area, this new period is known as Chalcolithic Age or Copper Age. [4]

In Copper Age, copper was not extracted directly from the outcrops, as ocurred in late Neolithic Age. Instead, It could be extracted from oxide or carbonate ores which were smelted in furnaces. Although oldest furnaces have been dated from 5000 to 4000 BC, copper was not extracted from ores, as in later furnaces, but from the native metal found in the outcrops. What made the difference and what allowed a higher production was not the process by which it was obtained but the fact that it could be extracted from new sources, the ores.

The extraction of copper from ores was a huge step in the evolution of human society. Chalcolithi Age began with it, as wells as the first great civilazations did. In the Tigris and Euphrates area, the first city-states started to appear, like the summerian city of Uruk, which later would led to the cuneifom script, to the Akkadian Empire in the Bronze Age and ultimately to the Babyloian Empire. Meanwhile, another kingdom was goint to be unified by King Menes along the Nile, starting a threee millennia serie of dynasties that would give one of the ancient Wonders.

As it has been mentioned, the extraction of copper from native outcrops crystals was a restriction to the tools and articles that could be manufactured with this material, and the use of furnaces removed this limit. The examples of the biggest copper objects that were cited before were produced by Pre-Columban Indians from the Ohio Valley and are dated from 200 BC to 600 AD. Although it was not the single reason that made civilizations, like the two mentioned before, and not the Indians to growth, it is clear that early cities needed and higher production of materials than the pre-columban primitive socities [2].

By 1855, at the Paris Exhibition, Henri Lucien Sainte-Claire Deville is showing the bars of aluminium that he has produced in its works at Javel, Paris. These aluminium bars are the first ones that have been industrially produced. Deville's process consist in a reduction process in which, in vapour phase, aluminium trichloride reacted with potasium, performing it in a small company that Deville establish in Saliendres. Three years later, in 1858, Deville starts to produce pure alumina from bauxite and not from the calcination of ammonium alum as it had been doing. Aluminium would be industrially produced by Deville's method or variations of it until 1887, when an Austrian chemist called Karl Joseph Bayer would changed it. Bayer realized that Aluminium hydroxide could precipitate from sodium aluminate by seeding. This sodium aluminate could be obtained from from bauxite after a process of prussure leaching by NaOH solution or caustic soda. After this process, alumina was feed into electrolutic cells to obtain aluminium.

Bayer process is a key method in the production of the aluminium nowadays. By then, in late XIX century and early XX century, it increased the production of this metal four orders of magnitude, being of two hundres tonnes per annum in 1894 to over two million tonnes in 1945 [4]. New ways of extracting this non-ferrous metal from bauxite allowed this, and before that the change in alumina source from ammonium alum to bauxite allowed Bayer to make this discovery. Thanks to this, old industries could see a growth in their efficiencies and their production, like the textile one by which Bayer process was originally developed [5] . Also new industries could be born and growth, like the aeronautical one, as first aeroplanes evolved from being made of wood to aluminium alloys.

Early copper production in late Neolithic and early Ancient Age and Aluminium production developed by Deville and Bayer are two examples of new materials and extraction methods that have changed human society. However, all that glitters is not gold. Mining and metal production industries take roles in one of the biggest challenges that humans have to face int he 21st Century, anthropogenic greenhouse gas emissions and their consquences. Carbon dioxide is the main contributor to this effect, being released in processes like energy production by coal and fosil fuels. Looking at the Steel industry, only by its own it accounts for five percent of total anthropogenic carbon dioxide production, releasing an average of 1.9 tons per ton of steel produced [6]. In 2015, 1.6 billion tons of steel were produced [7], which means almost two billion tons and a half of CO2 emissions that contributes to global warming. Althoug global warming is of mean concern due to its negative effects to biodiversity and climate change, for example, it is not the only consequence of emissions. Thermohaline circulation shutdown, acidification of water due to carbon dioxide that solves into oceans, fusion of Artic, Antartic ice and glaciers or mean sea level rising are of main significance.

A good illustration of how emissions may effect human society are the side-effects of the mean sea level growth. As it is not known when anthropogenic emissions may stop, two sceneraios can be set [8]. In the best one carbon dioxide is at its lower concentration in atmosphere, releasing just one thousand gigatons of carbon dioxide. Under this asumption, by 2100 water level may grow up to one meter while in the worst scenario, where five thousand gigatons may be released, sea-level may reach up to five meters. Some data to make a clear picture of this; a sea-level rise of one meter would cover avout one million square kilometers of coastlands, half of these lands being from Asian Southwest, 34.700 from Europe and 62.000 from United States, which would come with population movements. 50 millions refugees would have to abandond their homes due to flood in Asia, 12 millions in Europe and 2.6 in United States. All of this would happen in the first one hundred years, lasting nine thousand years in a five thousand gigatons of CO2 released scenario with a total water rise of seventy meters. Although this is just a simplification, as population distribution and density may change until 2100, not to mention until nine thousand years. Social repercussions of mean sea-level growth and population movement would not be as catasthropic as it may sound at first, because it would be dispersed through long times. However, these figures are of some help in the understanding of sea-level rising consequences for humans being and the rearrangement that may imposse to society. And a five percent of the total CO2 responsible of this situation would be due to steel industry and a three percent to iron industry. Mining and metal production industries have also to reduced their enviromental footprint.

Although enviromental concerns are central in these times, what really moves industry and market are prices and production. Steel industry has seen its global production increasing until 2014, when it reached 1,670 millions of metric tons of crude steel, followed by a decrease in 2015 to 1,623 millions [7]. Despite the fact that some national industry productions have been falling from 2012, like the European one, the 2015 plunge is global. Some industries that were growing until then have started to see their first deccelerations in production, like Middle East, which have gone from a increase of 11.2% in 2014 to a -0.6%. In addition, and although steel production has been increasing until 2014, growth rates were smaller each year, going from a global production growth rate of 15.7 % in 2010 to a one of 1.2 % in 2014. These rates are even lower for some regional productions like North America, with a negative growth rate of -8.6%, Asia and Oceania, -2.2%, and European Union, -1.8%, having these three regions the biggest steel production in 2015.

Another figure of merit is the steelmaking capacity, which can be defined as the total production of steel in ideal conditions. Even with the dropping of the production and the growth rates, capacity has been increasing from 2005 until 2015, with a maximum of 2,634 millions of metric tons. This all means that withal having a potential production of 2,634 millions of metric tons, the annual production of steel in 2015 was 1,623 millions. According to the World Steel Association and to the USA Department of Commerce, the reason to the increasing capacity is that it has a lower response than actual production, so it is reasonable to expect a discontinuation to its growth and a decreases in future years.

Once total production, growth rate and potential production have been studied, it is time to focus in the global steel demand and its evolution. As it could be expected from a continuous growing society, steel demand has been growing exponentially until 2010. Since then, demand has been increasing too but at a lower rate. This stand off has been of greater importance in countries from North America and European Union and lower in countries from Asia, having its maximum in China [9]. In summary, steel industry production and growth rate have stopped and started to decrease while capacity is still increasing, but at lower rates and in sight of following actual production behaviour. In the other hand, demand is still increasing, altough at a slower rate than until 2010. Steel industry is weak according to the Organisation for Econominc Co-operation and Development [10]. There is an over-capacity that makes prices lower along with the reducing demand and profits are going down.

Though this summarized study is focused in steel industry, it is a close approach to mining industry context and metal refinement industry. Steel market is the bigest one, followed by aluminium, and in addition, It is highly influenced by iron which account for 39% of ore extraction. However, other metal extraction industries like nickel, which accounts for a 3%, manganese and chromite, both below 1%, are important as they allow alloys with better properties [11]. Gold and copper are also key metals, with a production of a 16% and a 13% respectively. Looking at Copper and aluminium refinement and north american extraction industries reports, they indicate similar results to the ones given by the steel market, with decreasing leading index of metal prices and growth rates [12].

As it has been stated at the beginning of this section, new methods to product materials and new ways and sources to extract them have driven economics and society along human history. Neolithic cultures were able to use copper cristal extracted from natural outcrops along with gold, as they are malleable metals that can be easily cold worked. However, iron has been found to be another metal that it was used, although it's harder to take from nature and to work. The technique to use it were subjected to its discovery inside meteorites and due to the high temperature at which it was found, it could be hammered out into tools.

All that is gold does not glitter and not all those who wander are lost. Maybe it is time to start using again these materials that are wandering in space. Asteroids are rich and lot of them are close enough to made extraction reliable. Mining could become cheaper, which could lead to a decrease in refinement of metals and therefore higher benefits. Precious metals like platinum could become a more common material which would change their market and their social contexts allowing its industry to evolve.

Asteroid exploitation could be advantageous not only to the mining and metal industry but also to space exploration as metals are not the only materials that could be obtained. Water can be extracted from asteroids, which would be useful in order when using it in cooling systems or maybe hydrogen and oxygen could be obtained from this water. This oxygen might be used in life support systems or as oxidizer, hydrogen could be used as fuel and carbon, along with the oxygen, could make also possible refueling of monopropellant system. Making all this possible woulg give place to longer and cheaper missions and to a lower maintenance price in Earth-orbit stations as they would become more independent. A new industry could be stablished in lower space thanks to refinement of metals obtained in space and, therefore, construction and production in orbit. Of course, emissions and enviromental impact would be lowered too. Science could also see rewards from the mining of asteroids, for example allowing a deeper insight into the Solar System formation [13].

1.2 State of the Art

Asteroid mining is not an idea that came out of the blue, it's not a recent idea. There are some previous works that try to answer the question "Is it asteroids exploitation profitable or is it just a waste of resources?". One of the biggest troubles in the study of the financial rewards of the subject is that it is not an independent field to study. There are lot of areas that come into play in an entreprise like this: economics, legal rights and ownership, mining engineering, propulsion techonologies, astrodynamics and asteroid observations, among others. In this section, some of the present situations of these subjects are going to be stated, while astrodynamic and spectrum observation will be covered in their own chapters.

1.2.1 Legal Framework

Space, as any nation, is regulated and there is legislation that has been developed around it. The main principle that applies to Space is that no nation can reclaim its sovereignty, meaining that it belongs to all humankind. Any nation is free to explore outer space and conducts any space activities by its own without discrimination. All these principles are therefore regulated internationally by United Nations, and specifically by its Office for Outer Space Affairs which is regulated by the Committee on the Peaceful Uses of Outer Space (COPUOS), which was set up for the first time in 1959[1]. It is divided into the Scientific and Technical Subcommittee and into the Legal Subcommittee, which is the one that takes part in the the legal framework[2]. At that

[1]http://www.unoosa.org/oosa/en/aboutus/structure.html
[2]http://www.unoosa.org/oosa/en/aboutus/history/index.html

time, it was formed by 24 member states but nowadays it has grown up to 84 members states, according to the General Assembly Resolution 71/90 [14], being United States, United Kingdom, Germany, France, Spain, Italy, Russia, China, India and Japan among them. In adition, there are some external observer organistasions like the International Air Transport Association (IATA), the International Institute of Space Law (IISL), the European Space Policy Institute (ESPI), the International Astronomical Union (IAU) or the Planetary Society.

Since 1959 and the birth of the COPUOS, two treaties have been conclued and ratified by the ONU member states. The Treaty on Principles Governing the Activities of States in the Exploration adn Use of Outer Space, including the Moon and Other Celestial Bodies was adopted by the General Assembly the 19th December 1966, it entered into force in 10th October 1967 and their depositaries were Russian Federation, United Kingdom and United States [15]. Article I from the annex of this Treaty states the next:

The exploration and use of outer space, including the Moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind.

Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States without discrimination for any kind, on a basis of equality and in accordance with international law, and there shall be free access to all areas of celestial bodies.

There shall be freedom of scientific investigation in outer space, including the Moon and other celestial bodies, and States shall facilitate and encourage international co-operation in such investigation.

Conclusions that come out of this Article are pretty clear. Space is the province of all mankind and any activity and scientific investigation has to be done toward the human benefit and not national nor private profit.

Later, in 1979 General Assembly adopted in resolution 34/68 the Agreement Governing the Activies of States on the Moon and Other Celestial Bodies [16]. At the beggining of its Annex it can be read the following:

The States Parties to this Agreement, [...] bearing in mind the benefits which may be derived from the exploitation of the natural resources of the moon and other celestial bodies,

While, Article 11 states:

1. The moon and its natural resources are the common heritage of mankind, which find its expression in the provisions of this Agreement [...]. The moon is not subject ot national appropiation by any claim of sovereignty, by means of use or occupation, or by any other means.

Neither the surface nor the subsurface of the moon, nor any part thereof or natural resources in place, shall become property of any State, international intergorvermental or non-govermental organization, national organization or non-goverrnmental entity or of any natural person. The placement of personnel, space vehicles, equipment, facilities, stations and installation on or below the surface of the moon, inclugind structures connected with its surface or subsurface, shall not create a right of ownership over the surface or the subsurface of the moon or any areas thereof.[...]

This article turns to be more restrictive than the one from the 1966 Treaty. It clearly forbid mining, mineral extraction and ownership of surface nor subsurface of the Moon. Even so, it only refers to the Moon, taking into account others celestial bodies only in the foreword and saying no more about natural resources of these bodies. In addition, this Treaty was not signed by all the Member States, failing to this United States, among others.

Though both treaties are signed in 1966 and 1979, COPUOS and its Legal Subcommittee in the fifty-sixth session that took places in 23th March 2017 [17][3] have ratified both of them, so it can be concluded that mineral extraction is still regulated by them.

However, in 2015 at the 1st Session of the 114th Congress of the United States House of Representatives introduced an amendment "[...] to promote the development of a United States commercial space resource exploration and utilization industry and to increase the exploration and utilization of resources in outer space [...]"[4] . This amendment added a new chapter to United Sates Code, Chapter 513 - Space Resource commercial exploration and utiilization, Subtitle V of title 51 [18]. Section 51302 of this chapter states:

(a) In General.–The President, acting through appropriate Federal agencies shall: (1) facilitate the commercial exploration and utilization of space resources to meet national needs;

(2) discourage government barriers to the development of economically viable, safe, and stable industries for the exploration and utilization of space resources in manners consistent with the existing international obligations of the United States;[..]

In Section 51303, Legal Framework:

(a) Property Rights.–Any asteroid resources obtained in outer space are the property of the entity that obtained such resources, which shall be entitled to all property rights thereto, consistent with applicable provisions of Federal law and existing international obligations.

Nonetheless, European Union has not taken too long to create a legal framework about space resources exploitation. The Government of the Grand Duchy of Luxembourg has become the first state in EU to legislate about the matter, making a law that came into force on August 1, 2017[5]. Article 1 of this law states the next:

Space resources are capable of being appropriated.

The meaning of this article is pretty clear and there is no place for doubt or interpretation. In fact, the next sixteen articles of the law set the constrains and limitations, like fees to be paid, supervisions from the Government, the nature of the company and son on that the enterprise should follow in order to start and maintain an asteroid mining program. The new legislation ends with the eighteenth article, in which it sets penalties that should be suffered when contravening this law.

[3] $http://www.unoosa.org/documents/pdf/spacelaw/treatystatus/AC105_C 2_2 017_C RP07E.pdf$

[4] House Report 114th Congress 114-153

[5] http://www.spaceresources.public.lu/content/dam/spaceresources/news/Translation%20Of%20The%20Draft%20Law.pdf

The Amendent to the United State Code and the Law stablished by Luxembourg are clearly in oposition to UN treaties, which states that there has to be a international frame in prior to celestial exploration resources. Altough nowadays these activies are forbidden by these international traties, it seems that their validity is weak, as they were not signed by all the Member States and Government are starting to create their own legislation. Asteroid resources, therefore, are starting to attract attention of national administrations and private companies, like Planetary Resources, so farther changes in legal framework may be expected from now on.

1.2.2 Extraction technology and sample return missions

Mining, as it has been stated, is an ancient activity that humans have been performing since prehistoric times. Nevertheless, mining in Space has not count yet with such as experience as mineral extraction over Earth's surface. The main difference, and therefore the main trouble, when dealing with space is the appearence of zero gravity and, recalling Newton's Third Law of action and reaction, mining under this condition may becomes an even more serious business than usual mining. As one of the biggest and more masive bodies that can be located among Near Earth Orbits is 433 Eros (1898 DQ), with a bulk density of 2.67 g/cm$\hat{3}$ and a diameter of 16.84 km[6], recalling this time Newton's Gravitational Law and assuming a perfect spherical body, it would have a gravity two order of magnitudes below Earth's one. This concludes that in order to extract mineral from NEAs, zero gravity mining techonology is required.

Regolith Advanced Surface System Operations Robot (RASSOR) excavator is a "teleoperated mobile robotic platform" developed by NASA[7] [8]. Thanks to counterrotating bucket drums it is able to excavate under non-gravity conditions as it develops low horizontal reactions and almost no vertical forces. In this way, the extraction does not depends on traction or weight to provide a reaction force that counteract the ones that are being created by the exploitation. However, RASSOR is far from being actually reliable and fully developed and has not been yet tested in proper missions. Some tests at NASA's Kennedy Space Center in Florida were shown in October 2016[9].

Other works have studied the possibility of extraction minerals from different type of asteroids according to their minearology composition. When facing Carbonauceous Asteroid, Carbonaceous Asteroid Mining & PRocessor (CAMPR) could have a chance [19]. This system is composed of three miners which obtain energy from a nuclear power plant and load extracted mineral into three flying hoppers. This CAMPR is aimed to land into predetermined areas which previously ores haven located and anchor to surface with the use of helical anchors. Once at the surface, it use an helical boring tool and intese microwaves [20] [21] in order to break the ore. For the extraction from metallic asteroids of type X and M, a multiple blade rotating cutter head is proposed.

Nontheless, water could be also extracted from asteroids instead of metals, carbonaceous or silicate minerals. Kuck's process proposes the use of a light drill-rig [19], a fluids collection bag

[6] *https://ssd.jpl.nasa.gov/sbdb.cgi#top*
[7] *https://technology.nasa.gov/patent/KSC-TOPS-7*
[8] *https://technology.nasa.gov//t2media/tops/pdf/KSC-TOPS-7.pdf*
[9] https://www.youtube.com/watch?v=cRLnAeL3wdU

and filtration, pressurization and reheating systems in order to obtain liquid water by means of a light-weight system. Though the total mass of the system does no affect mining process, it definitively has to be taken into account as small multiplications of mass in space may lead to a vast increase in fuel mass, according to Tsiolkovsky Equation 1.1, and therefore in mission costs. Even so, regolith devolatilization process may be another option. Among the equipment required by devolatilization colletors, soil pressurizer, grindin mill, heaters, solid - vapour separators, colletor bags, tailings disoposal and gas cleaner may be found. Although extraction system becomes more complex, it is less efficient as water that may be extracted from soil minerals is not greater than the 10 % of the mass of the sample. However, this does not count with usuals problems that Kuck's process encounters, like the need of presence of subsurface volatiles or troubles associated with drilling. Devolatilization process suggest a mass throughput ratio of kilograms of material extracted per day per kilogram of system mass of 200.

$$\Delta v = v_e ln \frac{m_0}{m_1} \tag{1.1}$$

Studies have been done also in the field of continuous against discrete excavation [22]. Discrete excavators have to stop before doing new cuts and between surfaces contacts dumping load activities or clearing of cuting surfaces usually have to take place. Among discrete extractor prototypes NASA's Cratos or NASA's Centaur 2 which has been equiped with a 2-DOF front-loader bucket. RASSOR 1 and 2 are two examples of continuous excavators prototypes. Tests with continuous systems under reduced gravity conditions, 1/6 g, give extraction rates of 0.5 kg/s employing a system of 300 kilograms. A devolatilization regolith system of the same mass with the assumed ratio of 200 would give a rate of 0.69 kg/s.

Japan Aerospace Exploration Agecy (JAXA) mission Hayabusa has became the first mission ever that have returned samples from an asteroid. One thousand and five hundred particles of regolith dust with a size of a few microns were the specimen recollected by the prove using its Sampler Mechanism (SMP). This mechanism works by shooting five small spherical projectiles with a diameter of ten centemeters that lift dust from the surface that is collected by a tube and a collector. Though SMP is useless when trying to extract large masses from asteroids, Hayabusa contributed to a better understanding of mining in the absence of gravity.

Rosetta and its lander, Philae, can be considered also even as its target was the comet 67P/Churyumov-Gerasimenko (just Chury from now on) as sample collection was also aimed to be performed in non-gravity conditions. Rosetta mision, the first one that has landed on a comet, was launched in 2nd March 2004 and after a total six gravity assits and flyby at Eart, Mars and Steins and Lutetia asteroid, it arrived Chury ten years later in 5th August 2014. Philae landing attempt was planned to occurs in 12th November 2014 but, unfortunately, it could anchor itself to the surface and it bounced. Equiped with the Multi-Purpose Sensor for Surface and Subsurface Sciense (MUPUS) anchors and with an Active Descent System (ADS), Philase was supposed to use firts propulsion from ADS to avoid rebound at the touchdown while using MUPUS harpoons to lock to the surface. Due to this failure, the Sample and Distribution Device (SD2) finally could not use its drills, and it shown one of the main troubles of non-gravity conditions and the need of an anchor system.

JAXA, who were in charge of Hayabusa, looked for a second Hayabusa mission. In fact, it was launched the 3rd December 2014, its planned to arrive in 2018 and come back in 2020. The target of this new prove is the asteroid 1999 JU3 and, in order to arrive to it, an Earth flyby was performed in 2015. Although, as it is going to be explain later in Section , this maneuver seems to be similar to the one propossed in this work, Hayabusa 2 propulsion is done by an ionic engine and by a continuous burning. Sample collection system is going to be again the Sampler Mechanism SMP used in the previous mission. However, it is also provided with the Small Carry-on Impactor (SCI), which will shoot a 2.5 kg projectile to the asteroid surface in order to create a crater with a 2 to 7 meters diameter and in this way study inner composition of the asteroid.

NASA, in the other hand, is also looking for the return of asteroid samples. OSIRIS-REx was launched 8th September 2016 towards asteroid Bennu and its planned to return in 2023. It is equiped with the Touch-And-Go Sample Acquisition Mechanism (TGSAM) which would take among 0.06 and 2 kilograms of regolith in a touch and go maneouver that will take 5 seconds. This mechanism would also lift dust particles like the Hayabusa with the difference that it will use a nitrogen gas jet. Sample will be storaged inside the ORIRIS-REx Sample Return Capsuse (SRC)[10][11][12][13].

1.2.3 Previous works

As it was said at the beginning of this chapter, asteroid mining is not a new idea and it has been widely studied from diverse points of view. Some works have foccused on the economic viability of this enterprise by studying its Net Present Value (NPV)[14] and its Payback Period[15]. M. J. Sonter [23] analyzes NPV as a function of launch costs, mass returned from exploitation and mission times, expressed in NPV equation 1.2. Sonter concludes that the economic viability is driven by propulsion system characteristics, project times, ΔV requirements and time-cost-of-money. He also states that a delivering cost into Low Earth Orbit (LEO) of 200 $\$/kg$ or below will make celestial resources to be profitable.

$$NPV = C_{orbit} \cdot M_{mpe} \cdot f \cdot t \cdot r \cdot e^{\Delta v / v_e} \cdot (1+i)^{-(a^{3/2})} - (C_{manuf}\left((M_{mpe} + M_{ps} + M_{ic}) + B \cdot n\right) \quad (1.2)$$

Being

D. G. Andrews [19] defines a asteroid mining project architecture using a few key elements: Asteroid prospectors, launch systems, space operations centers and asteroid miners. Within these elements, this work also considers power generation and extraction technologies. Andrews et al

[10] http://danielmarin.naukas.com/2014/12/03/lanzada-la-sonda-japonesa-hayabusa-2-para-recoger-muestras-de-un-asteroide/

[11] http://danielmarin.naukas.com/2010/11/16/hayabusa-consiguio-su-objetivo/

[12] http://danielmarin.naukas.com/2010/07/07/el-polvo-de-hayabusa/

[13] http://danielmarin.naukas.com/2016/09/09/osiris-rex-ya-va-rumbo-a-recoger-muestras-del-asteroide-bennu/

[14] Measurement of the monetary flows that a project will generate in the future, calculating its present value as a function of discount rate and comparing it to inital costs

[15] Time needed until initial costs are recovered

C_{orbit}:	Launch costs [$\$/kg$]	i:	Market interest rate
M_{mpe}:	Mining and systems mass [kg]	a:	Semi-major axis of transfer orbit AU
f:	Mass Throughput ratio [$kg_{mined}/kg_{equipment}/day$]	M_{ps}:	Power supply mass [kg]
t:	Mining period [$days$]	M_{ic}:	Intrumentation and control mass [kg]
r:	Porcentage of valuable material recovered from the ore	C_{manuf}:	Specific manufacturing miner cost [$\$/kg$]
ΔV:	Return velocity increment [km/s]	B:	Annual budget [\$]
v_e:	Propulsion system exhaust velocity [km/s]	n:	Total project time $year$

consider that a requirement to asteroid mining is making accesibility cheap and short in periods. They assess 2007 PA8 asteroid due to its limited access due to the high orbit eccentricity and due to its compositional characteritics, being an Xc asteroid. As result, a total mission time of 1.8 years with a total ΔV of 7 km/s from the Space Operation Center, in L5 point, delivering a total mass of 200 mT. Assumiing a 10 % discount rate, this work gives a 35 % NPV in 20 years.

Shane D. Ross [24], using same NPV expression, equation 1.2, as Sonter [23], arrives to similar conclusions. However, he estimates that v_e or I_{sp} optimization does not necesary translate into more profitable projects, as chemical and ionic propulsion have different transfer times. Also, outbound ΔV is only a phisical parameter that limits launcher capabilities, while return ΔV should be minimized. Inside minimum total project time, transfer times should be the lowest possible ones, being mining season the longest ones available and therefore increasing the material substracted from the asteroid and returned to Earth. These results should give positive NPV trying to minimize uncertainty associated with future interest rates. Projects longer than three year should have a Mass Pay Back Ratio (MPBR) high enough in order to take bigger financial risks.

Due to its potential economic value, asteroid mining has brought private companies attention. Deep Space Industries[16] has been working in the field since 2013 and its work have focussed in a four phases project: prospect, harvest, process and manufacture. DSI is looking for the exploit of asteroids water due to its use in support life systems, manufacturing of radiation shields, use as propellant in its vapor state or as fuel when electrilysed. One of their key projects is the electrothermal thruster Comet-1, which uses water as propellant, as said before, obtaining an Specific Impulse of $150 - 170[s]$ with a Specific Power of $2.52 - 2.8[W/mN]$ and a Specific Thrust of $0.360[mN/W]$[17]. Comet-1 offers two configurations compatibles with CubeSat, Comet-1-300 and Comet-1-750. They differ each other in dry mass, 350 g and 700 g respectively, and propellant mass, 300 g and 750 g. Six Comet thrusters were ordered in Q3 2016 in order to be delivered in Q3 2017. In their four phase project, DSI is still in the prospecting one. Prospector-X would be their first mission, in association with Luxembourg Government, being an experimental project that would be used to test key technologies, leading to Prospector 1, which would land and study asteroids in order to determine their value. Propector-X is planned to be launched in 2017 and It will use a Comet-1 thruster.

Planetary Resources, founded in 2009, can also be counted among private companies that are looking forward asteroid mining and its financial profit. Their main program is the Arkyd prospecting program, starting with the infrared telescope Arkyd-100 that is intended to detect

[16]http://deepspaceindustries.com/
[17]https://deepspaceindustries.com/technology/

NEAs from LEO. Prior to this spacecraft, Planetary Resources have been testing technologies through missions like the A3R, which stands for Arkyd 3 Reflight. The “reflight” part of A3R comes after the destruction of the original A3 in the failure launch of the Cygnus Orb-3 (CRS-3)using the Orbital Sciences’ rocket Antares 130 in 28/10/2014. A3R was finally launched on SpaceX Dragon SpX-6 (CRS-6) using Falcon 9R rocket, being deployed from International Space Station in July 2015 into a 90-day mission that testes avionic and controls systems. A6 is the next step into a fully operational orbital telescope and it is expected to launch two of these spacecrafts, being the first lift-off programmed in 2017 and using the indian PSLV-XL developed by ISRO. The second one has not been announced yet.

Trajectory optimization have been performed in previous NEA and missions. One of them has been already mentioned before, the Hayabusa II mission held by JAXA. This probe is propulsed by an assembly of four ion thrusters, though only three of them are going to work at the same time. The specific impulse of ITA (Ion Thruster Assembly) is of $2600 - 3000$ seconds, with a lifeime of over 18000 hours and a thrust of $5 - 3mN$. Hayabusa II was injected by H-IIA, its launch vehicle, into an orbit that after two continuous thrust maneuvers, with a total operating time of 511 hours, would deliver it after a year again to Earth. At this moment, it realized a gravity assist manuever at a surface altitude of 3090 $[km]$ that changed its orbit plane 80° and increased its velocity by 1.6 $[km/s]$[18]. Orbital velocity of the probe after the swing by manuever was 31.9 $[km/s]$. Encounter with asteroid 1999 JU_3 is estimated to happen in July 2018.

OSIRIS-REx[19], mission that has been mentioned before, would try to reach NEA Bennu by 2018, after being launched in September 2016 and an Earth gravity assits in September 2017. Like Hayabusa II, the Atlas V Rocket, the launch vehicle, gave to OSIRIS-REx a hyperbolic escape velocity of 5.4 $[km/s]$, sending it to an orbit sent it back to Earth after a flight time of a year. During this first trajectory leg, the probe realized a series of continuous thrust manuevers to increase its velocity in 0.52 $[km/s]$. The flyby maneuver turned the orbital plane of the trajectory, setting it into a rendezvous orbit with Bennu. However, additional ionic thrust would have to be perfomed in order to achieved the mentioned orbit. Finally, it will reduce its orbit by 0.53 $[km/s]$ in order to obtain a relative velocity with the NEA of 20 $[cm/s]$.

Going to asteroids is not the only possibility towards harvesting their resources. Shepherding asteroids have been also considered in plenty of works and articles like J.P. Shance and C.R. McInnes and Keck Institute for Space Studies ones [25][26]. Even this subject falls out of the scope of the present work, it has been considered of interest to the mater of question and it should be taken into account as an alternative. In fact, members from both Planetary Resources, Chris Lewicki, and Deep Space Industries, John Lewis, took part in Keck study[26].

[18] $http://global.jaxa.jp/press/2015/12/20151214_hayabusa2.html$

[19] https://www.asteroidmission.org/

1.3 Scope

The scope of this work is therefore to study possible trajectories that would allow asteroids exploitation and to optimize these orbits in order to make them profitable. It also considers socioeconomic impacts in the context stated before, the legal framework that regulates nowadays and how it would affect mineral extraction from this new source. Previous asteroid observation, its results and methods are also covered since, as it would be shown later, final values and benefits of asteroidal prospection depend drastically on target composition, volume and mass. The present wotk is divided in four different chapters.

- Introduction: The actual chapter, in which legal framework and state of extraction technology are addreesed. Trajectory optimization and sample return missions from NEAs are also covered in this first chapter. Socio-economic context and enviromental impact of the actual industry are also given.
- Asteroids and Nea Earth Objets: A definition of what is an asteroid and which of them are Near Earth Objects is stablished. The classificantion in terms of their orbital parameters is also explained, along with an spectral and minearologic taxonomy and their state of the art. It ends with the NEAs that are going to be analysed.
- Methodology: The database interface, which allows asteroid data to be used, and its development is covered. The four different anayliss (Lamber direct transfer, NSGA-II direct transfer, Lambert Flyby transfer and NSGA-II flyby transfer) that have been performed are explained in this chapter.
- Results and conclusion: The results obtained from the previous analysed and conclusion that can be extracted from them are described in this chapter. Future works and possible extensions to this work are proposed.

Chapter 2

Asteroids and Near Earth Objects

Inter Jovem et Martem
intrerposui planetam

Johannes Kepler

2.1 Definition

According to International Astronomical Union Resolution B5[1], "Small Solar System Bodies" are all objects in the Solar System that are no satellites, dwarf planets nor planets. Planets are defined to be celestial bodies that orbit around the Sun, have cleared the neighbourhood around their orbits and have sufficient mass for their self-gravity to overcome rigid body forces, having therefore nearly spherical shapes. Dwarf Planets definition is pretty close to that of planet, being different in the clearing of their neighbourhood, being Ceres an example with its orbit within the Asteroid Belt. All objects that do no fulfil one of these definitions are considered Small Solar System Bodies. This is a rough definition that does not give any insight about asteroid defitinion and does not explain why they are different to meteoroids, meteors or comets. However, Resolution B5 finds its importance in the fact that it recognize that definitions may change after new discoveries, surveys and observations. This idea is significant when studying asteroids, as new ones are found almost every day and their spectroscopic and family classification have to accommodate to them. But what is an asteroid? What is the difference between asteroids and comets? And between asteroids and meteoroids?

NASA has defined asteroids to be "relative small, inactive, rocky body orbiting the sun[2]". Once more, this definition by its own results to be ambiguous, but it may become more accurate if it comes with more data. One characteristic of asteroids is that their distribution inside Solar System is well defined and it is known with detail. Figure 2.1 was created at 2007 and it shows 159366 asteroids[3], which at that moment was the total number of asteroid with well defined

[1] $https://www.iau.org/static/resolutions/Resolution_GA26-5-6.pdf$
[2] $https://www.nasa.gov/mission_pages/asteroids/overview/fastfacts.html$
[3] $https://ssd.jpl.nasa.gov/?dist_ae_ast$

orbits, and it describes them by their dynamic characteristics and orbits. As it comes at first look, these asteroids may be gathered in families or groups and most of them have their semi-major axis, (a), in the range from 2.1 to 3.3 astronomical units (AU). The bast majority of asteroids encounters their orbits in this region of the Solar System between Mars, which has a semi-major axis of 1.5 AU, and Jupiter, which has an axis of 5.5 AU, however there exists a number of asteroids that are beyond Neptune orbit. This last family is considered to be part of the Trans-Neptunian Objects, with a semi-major axis of more than 30 AU. Due to the huge distance that separates them from Earth, this family fall outside of the scope of this work. A family of asteroids can be found between 5 AU and 5.5 AU which are called Trojan Group, they occupies stable orbits in Jupiter Lagrange Points L4 and L5, 60 degrees ahead of it and 60 degrees behind respectivly. Hilda family asteroids have a smaller axis, and they found their orbit in the third Jupiter Lagrange Point, which is in oposition to Jupiter. Below Hilda Family semi-major axis lay most asteroids. This region is called Asteroid Belt and also can be divided also into several groups. The inner of these groups are the Hungarian Asteroids, with a semi-major axis that goes from 1.7 AU to 2 AU.

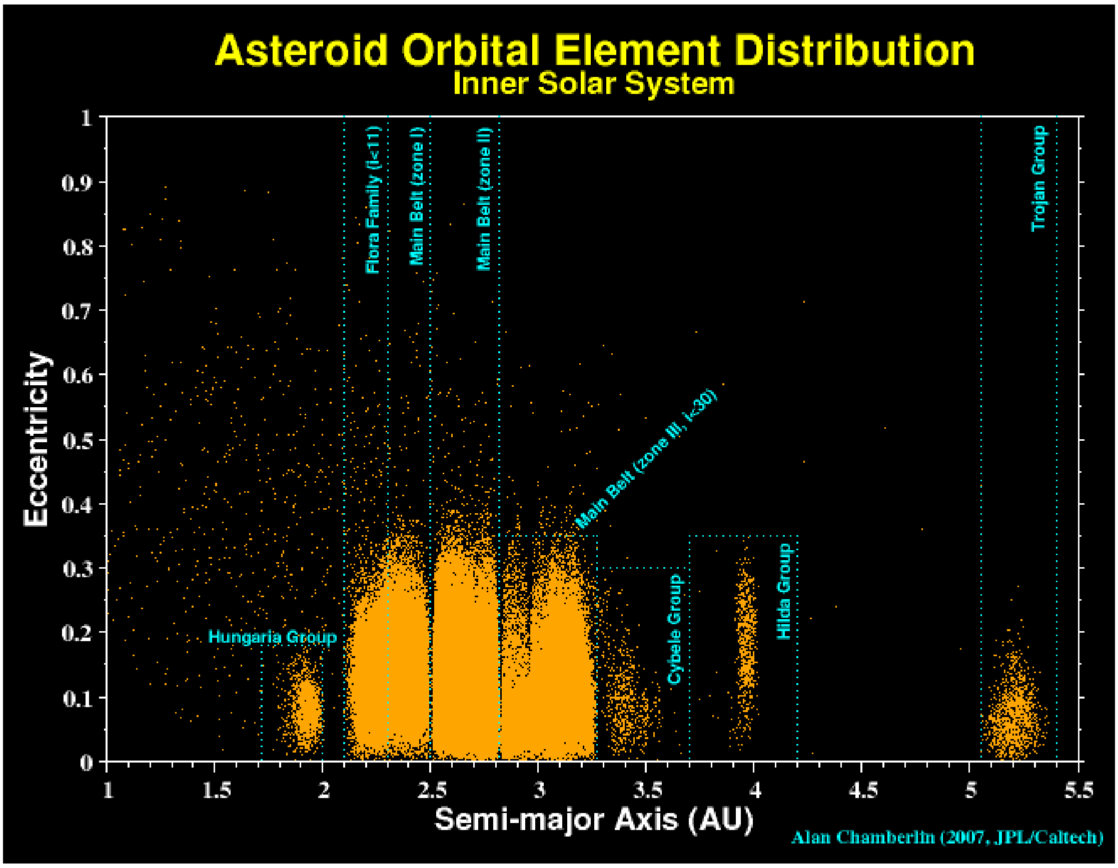

Figure 2.1: Asteroid Orbital Element Distribution.

A more detailed picture of what an asteroid can be formed now. Asteroids are relative small, inactive, rocky body orbiting the sun mostly between Mars and Jupiter. Nonetheless, there are asteroids whose semi-major axis is lower. This small group of bodies are the ones that have real interest to this work, and they are called Near Earth Objects (NEOs). NEOs are asteroids and comets that have a semi-major axis that is close to 1 AU and its perihelion distance (q) is below 1.3 AU. Asteroids with these features are considered Near Earth Asteroids, and the difference with comets is that these last ones are active, meaning that they have ice that could vaporize and therefore their mass may change over time.

Family	**Semi-major axis** [AU]
Trojan Group	5-5.5
Hilda Group	3.6-4.2
Cybele Group	3.3 - 3.6
Main Belt Zone III	2.8 - 3.3
Main Belt Zone II	2.5 - 2.8
Main Belt Zone I	2.3 - 2.5
Flora Group	2.1 - 2.3
Hungaria Group	1.7 - 2
Near Earth Asteroids	< 1.7

Table 2.1: Asteroids dynamic characteritation

Due to the huge amount of asteroids and the rate of their discovery (later some numbers about this would be given for NEAs), asteroids naming has to follow some nomenclature, as giving proper names to each one would be exhausting. Even so, there are some examples of asteroids with proper names like the first ones to be charted (Ceres, Vesta, etc), others named like famous characters (Mr. Spock or Frank Zappa) and others as a tribute, like the seven named after the Space Shuttle Columbia Disaster. In any case, Committee for Small Body Nomenclature (CSBN)[4] gives to each asteroid the year at which it has been discovered and two leters followed by further digits if they are needed. The first letter given to the asteroid corresponds with the half-month in which it was discovered, being A the letter for Jan 1-12 and Y the one for Dec 16-31. The second letter indicates the order in which it was discovered, being AA, for example, the first asteroid discovered in the first half of January. Letter I is not used in any case. The digits after the letters would be use after the use of the letter Z in the second position, returning to A. For example, 2005 VZ would be followed by 2005VA1.

One more distiction that will be helpful later is the difference between asteroids, meteoroids and meteorites. The first one has been already defined. Meteoroids are, however, small particles that come from asteroids or comets that orbit the Sun. If these particles enters the Earth's atmosphere, it begins to vaporizes and it leaves a light trail, which is called meteor. Finally, meteorites are meteors that survives the entry through the Earth's atmosphere and fall into its surface. A fact that is going to be useful when stablishing minearology classification.

Near Earth Asteroids are going to be the objects of interest in this work as their dynamic attributes make them potential target for low delta V transfers. Even so, this family encounters inside it different groups of bodies with their own orbit classification and if it is desired to extract minerals from them, a minearology classification is also desired.

[4]http://www.ss.astro.umd.edu/IAU/csbn/

2.2 Orbit Classification

In the previous section, a general definition of asteroid was given together with a small classification according to orbital parameters, like semi-major axis and perihelion. Although, in their majority, asteroids belong to the Main Belt region, being a total of 1.1 million to 1.9 million with a diameter larger than 1 kilometer and a millon with smaller diameters estimated to lay in this region. However, there is a considerable number of asteroids closer to the Sun. This group, already introduced, is named Near Earth Asteroids and at early September 2017 a total of 16609 NEAs have been discovered, being 1106 of them located this same year[5]. Since 1898, when the firtst NEA, 433 Eros, was charted, the rate at which these bodies has been found has grown exponentially, as it can be shown in Figure 2.2, thanks to programs like NEOWISE. As a result of these new NEAs discovery and of their regular observations, a Near-Earth Asteroids categorization have been performed. Nowadays, it is estimated that a 90% of NEAs larger thatn 1 kilometer have been found, focusing now the NEO Program in the discovery of the 90% of asteroids larger than 140 meters[6].

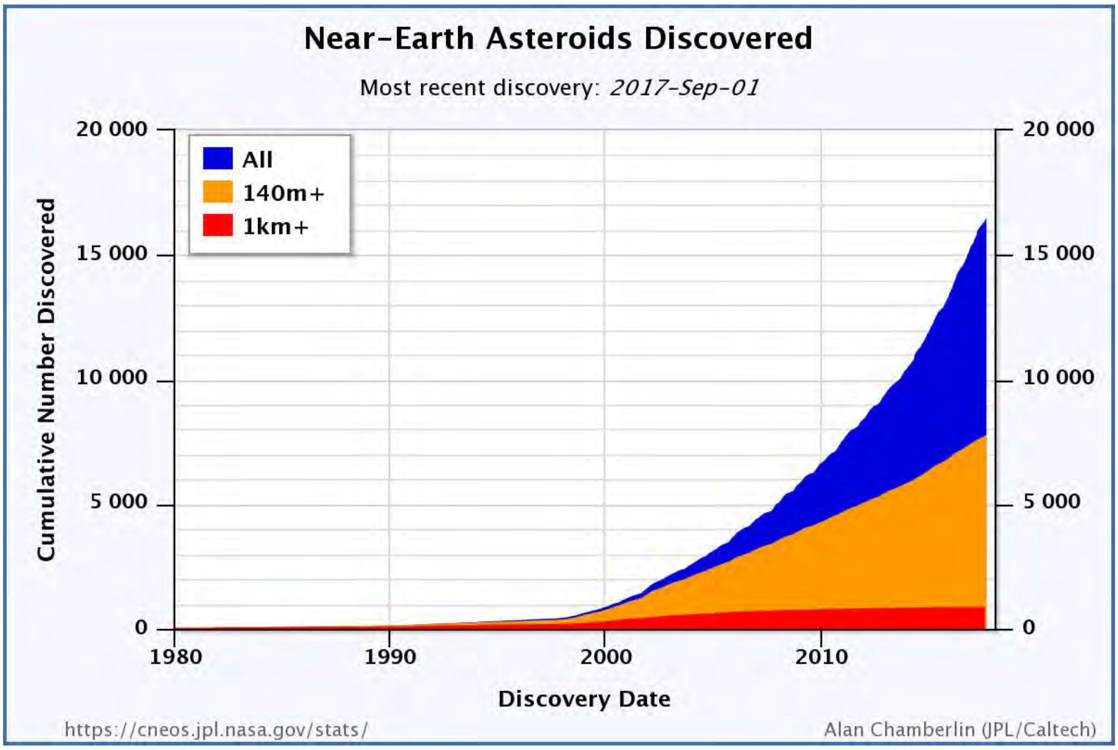

Figure 2.2: Near-Earth Asteroids Discovered

After 433 Eros (1898 DQ) was discovered, in 1898 by Carl Gustav Witt in Berlin, 887 Alinda (1918 DB) was discovered by Maximilian Feanz Wolf in Heidelberg, then in 1929 1627 Ivar (1929 SH) by Hertzsrpung in Johannesburg and 1221 Amor (1932 EA1) by Delporte in Uccle [13]. This last one, gives name to the family at which all of them belongs. This dynamic family is characterized by its high eccentricty, having a perihelion that goes from 1.017 AU to 1.3 AU

[5]http://www.minorplanetcenter.net/
[6]https://cneos.jpl.nasa.gov/stats/

and a semi-major axis higher than 1 AU. Therefore, asteroids from Amor Family does not cross Earth's orbit but they go through Mars' one, as Mars' aphelion goes up to 1.38 AU. This may cause gravitational perturbations, changing in this way NEAs orbits.

In the other hand, there are two dynamic families of NEAs that actually cross Earh Orbit. These two families are called after asteroid 1862 Apollo (1932 HA) and after 2062 Aten (1976 AA). Apollos asteroids have aphelions (Q) of even 2.29 AU and perihelions that go to 0.65 AU, passing through Mars, Earth and/or Venus orbit. Atens, in their counter part, have their perihelions inside Earth's orbit, being their aphelions greater than 0.983 AU. Other difference is that while Atens semi-major axis is lower than 1 AU, Apollos one is greater than 1 AU.

There is a fourth family, which owns his name to 1963693 Atira (2003 CP20). This family is similar to Atens in the way that their semi-major axis is lower than unity but make their difference in the fact that its perihelion is below 0.983 AU, being therefore their entire orbit contained inside Earth's Orbit[7].

Family	Atiras	Atens	Apollos	Amors
Definition [AU]	a < 1 Q < 0.983	a > 1 Q > 0.983	a > 1 q < 1.017	a > 1 1.017 < q > 1.3

Table 2.2: Asteroids dynamic characteritation

$$a \equiv \text{Semi-major axis } [AU] \quad q \equiv \text{Perihelion } [AU] \quad Q \equiv \text{Aphelion } [AU]$$

In summary, NEAs can be catogerized as in Table 2.2 according to their orbit parameters, which is a good starting point when studying its accesibility and feasible mining epochs. These epochs are going to be determined by the relative position of the asteroid with respect to the Earth and the time that takes to consecutive relative positions, which may be measured by Synodic Period, T_{syn}[27]. This figure is going to look for the time that takes for the body target to pass again through a position relative to the body of reference, being in the first one the NEAs and the second one the Earth in this work. For sure, this period by its own should not be taken into account when measuring energetic costs of the transfer orbit, but there is no doubt that mining asteroid programs would have to consider it also. T_{syn} would vary as a function of target's period and Earth's period, as Equation 2.1 shows [27]. From Kepler's Third Law, which relates the semi-major axis to the period, synodic period can be obtain as a function of the semi-major axis, a.

$$\begin{aligned} T_{syn} &= \frac{2\pi}{n_{Earth} - n_{NEA}} = \frac{T_{NEA}T_{Earth}}{|T_{NEA} - T_{Earth}|} \\ T_{NEA} &= \frac{2\pi}{\sqrt{\mu}} a_{NEA}^{\frac{3}{2}} \end{aligned} \tag{2.1}$$

Finally, the main parameter that is going to increase energetic cost, given in terms of Δv, is the orbital inclination. Going to an asteroid that has a similar orbital inclination means that the plane, which contains both the conical trajectory and the NEA's orbit, is going to remain

[7] $https://cneos.jpl.nasa.gov/about/neo_groups.html$

almost unchanged. In the other hand, going to orbits with different values of their inclination involve a plane change, a variation in the direction of the angular momentum, being these kind of maneuvers the most expensive in terms of Δv. For example, a change of 1 degree in low earth orbit, in a cirular orbit at 400 kilometers with a velocity of 7.67 km/s, would require 7.35 km/s according to the maneuver described by 2.2 .

$$\Delta V = v \; sin\left(\frac{\Delta\theta}{2}\right) \tag{2.2}$$

2.3 Compositional types and size and mass determination.

Aside from dynamic parameters, Near Earth Asteroids can be categorized based on their spectroscopic characterictis and on their absorption spectra. The basics of spectroscopy are widely known, light is absorbed or emitted by an object but at certain wavelengths this light emission or absorption does not occure. In an absoption spectra, light is reflected by a body but at some wavelenghts it is absorbed, as mentioned before, giving therefore a characteristic band pattern. Through years there have been survey programs that have been gathering spectral properties from asteroids, like the Eigh-Color Asteroid Survey (ECAS). From the spectral information derived from ECAS survey, in which four hundreds asteroids were observed in a wavelength range from 0.31 μm to 1.06 μm, David J. Tholen [28] propossed one of the first taxonomies in 1984. Three main groups were assigned; C-group, which were correlated to dark carbonaceous objects; S- group, being silicaceous objetcs; and X-group, belowing to it metallic objetcs.

Small Main-Belt Asteroid Spectroscopic Survey, or SMASS[8], is an asteroid survey program associated to MIT that observes and study spectral properties from asteroids. Thought its name only refers to Main-Belt Asteroids, they also work with Near Earth Asteroids as this program has gone trough two phases [29]. The first one, between 1991 and 1993, which resulted in measurements of 316 small/medium size in visible and near-infrarred spectrum from the inner-main belt. The second phase, which started at 1993 and ended in 1997, studied spectral information mainly from 1190 asteroids (being 74 of them NEAs). It covered also Near-Earth Asteroids and Mars-crossing asteroids [29], and it tried to reduce this data to study the correlation in composition between dynamic families. SMASS-II, as it is called the second period, was carried out using Hiltner and McGraw-Hill telescopes, in Arizona, using the Mark-III CCD spectrograph along with one of two CCD cameras and reduction was performed using the Image Reduction and Analysis Facility. Spectral parametrization was done using multivariate analysis PCA, Principal Component Analysis, which is described in Bus Phd Thesis [29] along with a full description of SMASS-II. Results derived from this observation, reduction and parametrization process led finally to a new taxonomy, the Bus System, with a total of 26 classes as a function of the spectral slope, the Principal Component 2 PC2' and the Principal Component 3 PC3'.

Since then, some iterations of this new taxonomy have taken place, being SMASS NEO one of them [30]. In this new phase of the SMASS program, previous measurements were extended with

[8] http://smass.mit.edu/smass.html

visible wavelength measurements done using a Double Spectrograph on the Palomar Observatory Hale telescope [31], and the RCSP spectrograph[9] on the Kitt Peak National Observatory Mayall telescope[10]. Infrared measurements were done using the NASA Infrared Telescope Facility, IRTF, in the SMASSIR survey [31]. Taxonomy derived from Binzel et al work and from Bus work are presented in Table 2.3, along with the number of NEAs sampled by SMASS in the first work[30].

Buss Class	NEA SMASS Sample	Buss Class	NEA SMASS Sample
A	1	R	1
B	5	S	76
C	13	Sa	2
Cb	3	Sk	13
Cg	1	Sl	6
Ch	1	Sq	62
Cgh	—	Sr	12
D	4	T	5
K	7	V	14
L	7	X	31
Ld	2	Xc	6
O	6	Xe	2
Q	18	Xk	9
—	—	U	3

Table 2.3: Buss Taxonomy [29] [31]

Although works presented before depends almost entirely in absorption spectras, there is another parameter that has to be considered, the albedo. When light strikes an object it can be absorbed of reflected, the ratio between them is what is called albedo. When measuring this ratio from an asteroid, it is observed that it is not constant over time. This effect may be due to two different reasons. The first is the shape of the asteroid, as perfect spheric objects reflects constant light along their rotation period but ellipsoids show varying albedos as the surface that reflects the light towards the observer is changing. The other difference in albedo measurements is due to changes in surface's reflectance due to color or composition. So the question now is how to difference among these two effects? Here enters the measurements in infrared band. If the reflectance changes, that means that more light or energy is being absorbed by the object so it becomes hotter, therefore if albedo goes down but infrared emissions show ups the conclusion extracted is that the surface composition or color is different, if not, shape is different. Of course, this becomes more complex as, for sure, both shape and color changes. In addition, Bus shows in its thesis[29] that spectroscopic characteristics and albedo are correlated. In fact, Tholen used albedo to differenciate among the X-class subgroups of its taxonomy [13].

Although even data taken from previous work gives an useful taxonomy, considering also spectroscopy from meteorites gives possible minearology composition, for example SMASS-I results showed similar spectras between S-type asteroids and achondrites meteorites. Bus

[9]https://www.noao.edu/kpno/manuals/rcspec/rcsp.html
[10]https://www.noao.edu/kpno/usrhnbk/user-toc.html

compares in its thesis its results with spectrum results from meteorite measurements made by Gaffey[32]. As result of this process, Bus found trends between asteroid taxonomy and meteorites classes, being L- and LL-type chondrites spectra similar to Q asteroid class, or CM chondrites similar to C-type asteroids. Binzel et al. [30] from SMASSNEO and SMASSIR also correlate S-type and Q-type with chondrite-like materials altough reddnened may give misinterpretations and mislead to ordinary chondrites. J. de León et al indicate high correlations between NEAs and LL-type chondrites[33]. Jeffrey S. Kargel [1] indicates that average H-chondrite meteorites contatins about 18.7% of iron-nicke metal which contains 28 part per million of precios metal, while LL-chondrites goes down from 1.2% to 5.3 %, meaning a range of 50 to 220 ppm of precious metal. Results from Kargel study are shown in table 2.4. In the other hand, a more recent study from P. V. Sukumaran et al gives values of 50-60 ppm of PGM to LL-type while C-type stands for 50-220 ppm of PGMs [34].

Metal	**Abundance in H-Chondrite [ppm]**	**Abundance in LL-Chondrite [ppm]**	**Abundance in iron meteorite [ppm]**
Ruthenium	5.8	17.8	21.5
Rhodium	1.1	3.3	4.0
Palladium	4.5	14.0	16.5
Osmium	3.9	12.1	14.5
Iridium	3.9	12.0	14.0
Platinum	8.0	24.7	29.0
Gold	1.1	3.5	0.6

Table 2.4: Abundances of Precious Metals in Meteorites and Asteroids[1].

Actually, there are some troubles in the use of this method. First of all, is the bias due to space weathering processes. It has been said along the section that the information is obtained from light that is reflected by the object, that is, the spectra. Spectral Slope is one of the parameters used in the analysis of the spectra information, It is the change in reflectance as function of the incidence wavelenght. It has been observed that this slope may change in time due to space weathering processes. Celestial body surfaces may be changed due to depositions of submicroscopic iron (SMFe) [30] and solar and cosmic wind ion irradiation. Asteroid life time may has its influence in this weathering process, as older surfaces get reddened with age due to SMFe acumulation, but also size. Younger asteroids show less reddened surfaces and greater dispersion. However, J. de León et al [33] also suggests that different compositions may lead to different weathering times, as olivines are more sensitive than orthopyroxene, for example. Their work concludes that a combination of both composition and size should be considered.

Second trouble in meteorites/asteroids comparison is the access to the firsts. In order to get a meteorite, it has to enter the atmosphere, it has to survive to this entry, otherwise it would be a meteor, and it has to also survive crash against Earth Surface. This sequence of events is potentially introducing a bias towards harder meteorites, which may lead to the asumption that this kind of objects are more common than more volatile ones among asteroids[13].

Celestial observation and measurement of light reflected by them has been done through years and employing different parameters and methods, like spetra or albedo analysis. Another process is by looking to the brightness of the bodies. Hipparchus of Nicaea was first in classifying stars according to their brightness. He arrived to the idea of using veils and look for stars that dissapear if looking through it, giving to them “magnitude 1”. He iterated this six times, classifying a total of 850 stars in 48 different constellations with any instrumentu but its own eyes and the six veils. Centuries later, John Herschel, son of the Neptune's discoverer William Herschel, questioned himself what was the difference between the light reflected by objects of different magnitudes. Using newtonian telescopes, he was able to monitor light, just varying mirror's diameter. Trying to get same brightness of dissimilar magnitude stars just by changing telescope's reflectors, he arrived to the conclusion that each step in magnitude is equivalent to a 2.512 brighter objetc, and that the difference between a magnitude 1 and a magnitude 6 was that the second reflects 100 more light than the first. Thanks to this, Norman R. Pogson was able to deduced the logaritghmic scale that is used nowadays to calculate apparent and absolute magnitude [35].

Apparent magnitude is the brightness of a celestial body as an Earth Observer sees it. This is a function of the size of the object, as bigger bodies reflect larger amounts of light than smaller ones, but also of the distance, being brighter closer objects than far ones. Notize that lower magnitudes mean brighter bodies, being –13 the magnitude of full Moon and -26.74 Sun's magnitude. In its contrary, absolute magnitude is the luminosity that the same object would gave if observer at a distance of 10 parsecs, 32.6 light years. Thanks to this, distance is not a parameter anymore, being magnitude just a function of size. A. W. Harris and A. W. Harris[36] came out with an expression, Equation 2.3, that estimates diameter, D , as function of the albedo, a, and of the absolute magnitude, H.

$$D = 10^{0.5[6.259 - log_{10} a - 0.4H]} \tag{2.3}$$

Albedo and absolute magnitude provide a powerful tool to estimates rough spherical diameters that along with spectral information lead to composition, mean density and therefore an initial estimation of the mass. Withal, this approach relies in asumptions like spherical bodies, which is far from reality and its associated with potential uncertainties. James L. Hilton [37] proposes size and mass determination bases in spacecrafts encounters with asteroids along with adaptive optics techniques and radar time delay-Doppler observations of binary asteroids and their dinamics and orbital perturbations.

2.4 Asteroids considered

Last sections intended to present the actual state of those fields and to give some foundations and criteria in order to choose asteroids for this case of study. According to what has been explained before, asteroids should be choosen as a function of their composition and dynamic parameters. Table 2.5 shows a total of twelve NEAs, whose optimum transfer trajectory will be study in this work. Among them, a total of three belong to Amor Family and one to Aten. However, first fourth NEAs have been choosen due to the availabity of information about their masses, densities, shapes, composition and spin rate. This last parameter is not a matter of study in this work but should be taken into account in an analysis of the suitability of NEAs to be mined. In figures B.1 - B.12, from Appendix B, NEAs orbits are plotted projected over Ecliptic Plane's, so for a complete interpretation of these figures consider inclinations given in Table 2.5.

As it can be seen in the table mentioned before, all the NEAs that are going to be studied have a semi-major axis lower than 2 [AU]. This value goes from 0.64222 for 1999 KW_4 to almost 2, being 1.9271 [AU] for 2000 UG_{11}. However, each semi-major axis fulfil the characteristics described in Table 2.2. Eccentricity of each asteroid, in the other hand, can be very different from one NEA to other, going from almost circular orbits for 2008 HU_4 and 2014 EK_{24} to highly ecliptic orbits like 1999 KW_4. Small inclinations are desired, nevertheless, 1898 DQ and 1999 KW_4 have 16.84°and 38.88°respectly, which will be interesting just as an analysis.

With the previous selection, diversity in orbits has being looked for. Among them, there are circular and almost coplanar orbits; like the one of 2008 HU_4; high eccentric and with a high inclination angle, like 1999 KW_4; or circular ones but with a high inclination, like 2014 EK_{24} or 2013 PA_7. However, and as said before, minearology and spectroscopy class would be important in a mining project. Therefore, some NEAs whose density, mass, size and shape information is known have been included.

Synodic period, which is shown in Table 2.5, would reflect time that would separate optimum transfer. According to Equation 2.1, NEAs whose orbital period becomes closer to one year, would have higher T_{syn} as denominator $|T_{NEA} - T_{Earth}|$ would approach zero. Values higher than one year would goes to an assymptotic value of 365 days. Due to this, 2014 EK_{24} has a Synodic Period of around 101 years in an orbit very close to Earth's one and very similar to it. Although this may indicates that optimum mining periods would be really separates among them, this might not be as bad at could seems at first. Due to its similitude with Earh's orbit, Δv variations through the entire synodic period may not be as differents as in asteroids with higher eccentricity, inclination or semi-major axis.

NEA	Dynamic Family	Semi-major axis, a $[AU]$	Eccentricity, e	Perihelion, q $[AU]$	Aphelion, Q $[AU]$	Inclination [°]
433 Eros (1898 DQ)	Amor	1.4579	0.2226	1.1334	1.7824	16.84
66391 (1999 KW4)	Aten	0.6422	0.6885	0.2	1.0844	38.88
185851 (2000 DP107)	Apollo	1.3652	0.3765	0.8511	1.8793	8.6717
494658 (2000 UG11)	Apollo	1.9284	0.5725	0.8243	3.0325	8.9236
459872(2014 EK24)	Apollo	1.0068	0.0699	0.93630	1.0772	4.8041
— (2014 SC324)	Apollo	1.9271	0.5250	0.9153	2.9390	1.6539
162173 Ryugu (1999 JU3)	Apollo	1.1895	0.1903	0.9632	1.4159	5.8839
253062 (2002 TC70)	Amor	1.639	0.1967	1.0997	1.6386	2.1470
— (2011 CG2)	Apollo	1.1774	0.1585	0.9907	1.3642	2.7571
— (2001 QC34)	Apollo	1.1283	0.1875	0.8167	1.3398	6.2355
— (2013 PA7)	Amor	1.1539	0.0874	1.0529	1.2548	3.4737
— (2008 HU4)	Apollo	1.0714	0.0556	1.0118	1.1310	1.3911

NEA	Spectroscopy Class	Diameter $[Km]$	Density $[g/cm^{-3}]$	Mass $M_{\odot}$	Period $[years]$	Synodic Period $[Years]$
433 Eros (1898 DQ)	S	16.84	2.67^*	$3.6 * 10^{-15*}$	1.76	2.31
66391 (1999 KW4)	S	1.317	2.4^*	$1.1 * 10{-}18^*$	0.51	1.04
185851 (2000 DP107)	—	—	1.6^*	$2.2 * 10^{-19\ *}$	1.6	2.67
494658 (2000 UG11)	—	—	1.5^*	$5 * 10{-}21^*$	2.68	1.59
459872(2014 EK24)	—	—	—	—	1.01	101
— (2014 SC324)	—	—	—	—	2.68	1.59
162173 Ryugu (1999 JU3)	Cg	—	—	—	1.3	4.33
253062 (2002 TC70)	—	—	—	—	1.6	2.67
— (2011 CG2)	—	—	—	—	1.28	4.57
— (2001 QC34)	—	—	—	—	1.20	6
— (2013 PA7)	—	—	—	—	1.24	5.17
— (2008 HU4)	—	—	—	—	1.11	10.09

*Eros mass determined by gravitational perturbation. 1999 KW_4, 2000 DP_{107} and 2000 UG_{11} determined by radar time delay-Doppler[37].

Table 2.5: NEAs to be studied

Chapter 3

Methodology

> The entire universe has been neatly divided into things to (a) mate with, (b) eat, (c) run away from, and (d) rocks
>
> Sir Terry Pratchett

3.1 Perl Interface HORIZONS-MATLAB

Asteroids' Ephemeris used in the present work have been extracted from the HORIZONS System. This program developed by NASA Jet Propulsion Laboratory from the California Institute of Technology [1] allows on-line ephemeris computation by request. Although a total of three different interfaces of free disposal (via telnet conection, email or web) are granted by JPL, they were found quite restrictive a priori. The idea behind this interface is that of being able to request and refine in an autonomous way any number of NEAs ephemeris for their use with MATLAB.

Besides JPL Horizons System, NASA Navigation and Ancillary Information Facility (NAIF) provides SPICE Toolkit, which gives a full set of functions and algorithms that are commonly used. This API is compatible with C, FORTRAN, IDL and MATLAB programm languages, being the last one (called MICE) the used in this work. Among the utilities at which MICE gives access, conversions between Coordinated Universal Time, ephemeris time and Julian Date or ephemeris computation can be found. SPICE use packages of information called kernels, which are key in working when working with it, as it needs to access information provided by them. These packages can be different nature according to their structure, for example, SPK kernels are the ones that supply spacecraft, planets, satellites, comets or asteroids ephemeris, while IK kernels stands for Instrument Kernels, giving information about them. Although this might looks like a solution to the asteroids' ephemeris problem, sadly NAIF does not count with a fully updated database of NEAs. However, in order to determine Earth position and velocities

[1] https://ssd.jpl.nasa.gov/?horizons

SPICE's tools and kernels have been used.

One approach to the interface problem may be the telnet interface, which was considered at the beginning. One of the utilities of the Telnet conection is that it allows users to create their own SPK files with the desired information. Along with this option, telnet can be automatize using *Expect* scripts, wich are extensions of *tcl* language, to produce batch series of data requested by users. Creation of SPK files has been not used because it would required a deeper understanding of SPICE enviroment, taking longer times than the available for this task. However, this approach would be more suitable and desirable if time was not a constrain, as it allows a direct interaction with MICE tools. The development of *Expect* scripts was also considered, but their outputs are hard to refine into MATLAB readable formats, being provided through FTP conections, via e-mail or Kermit.

E-mail interface relais on plain ASCII mail clients. Requesting is done by sending an e-mail to *horizons@ssd.jpl.nasa.gov* with the expresion "JOB" as subject and a predetermined format. Outputs are sent back from HORIZONS, fact that makes difficult the extraction of the information. Finally, the third option given by JPL is a web interface in which users define their request and select the output format; being HTML (the default one), plain text or a downloable txt file the three ones availables.

Although these are the three options that JPL offers at first, there is an additional way to send requests. This method uses as reference email's requirements format, which are going to be converted into an specific url. Making use of this url in any navigator, it displays a plain text with the desired output. The key in this method is that it can be automatized using *perl* language, leaving to it the requesting, storing and refining of asteroids' ephemeris.

HORIZONS System follows a predetermined style in its requests[2] that allows an easy and autonomous manipulation. In the case of this study, what it was desired was to obtain ephemeris for several asteroids in the same date period, with an equal time step, systems of references and output formats. Therefore, the only parameter that varies in each request would be asteroid's denomination. The nomenclature that has been followed in this step, the CSBN one, it is already explain in Section Asteroids 2.1, while NEAs designation has been obtained from IAU Minor Planet Center Database[3][4][5], being updated nearly every day with every new discovery. An Eros 433 (1898 DQ) request for epoch 2020-01-01/2029-12-31 is diplayed next. The example has been divided into columns just to clarification, command `STEP_SIZE = '1 d'` would follow on a new line `STOP_TIME = '2029-12-31'`.

The first statement `COMMAND` ask for the designation of the NEA, being the CSBN nomenclature accepted by it. `MAKE_EPEHM` allows the generation of the ephemeris, while `TABLE_TYPE` specified the format at which it is going to be provided. `CENTER` and `REF_PLANE` stablish withrespect which origin the vectors are referred and the plane of reference, the Ecliptic One in that request and being `500@10` the Sun. The next three commands, `STAR_TIME`, `STOP_TIME` and `STEP_SIZE`, are used to define the epoch of study and the sample size.

[2] $ftp : //ssd.jpl.nasa.gov/pub/ssd/horizons_{b}atch_{e}xample.long$
[3] http://www.minorplanetcenter.net/iau/lists/Atens.html
[4] http://www.minorplanetcenter.net/iau/lists/Apollos.html
[5] http://www.minorplanetcenter.net/iau/lists/Amors.html

REF_SYSTEM fix system of reference of the epoch. VEC_TABLE defines the outputs that are going to be provided, in this case "position" and "velocity", while OUT_UNITS specifies its unit and CSV_FORMAT gives them as comma-separated values.

```
!$$SOF
COMMAND= '1898 DQ'
MAKE_EPHEM= 'YES'
TABLE_TYPE= 'VECTORS'
CENTER = '500@10'
REF_PLANE  = 'ECLIPTIC'
START_TIME = '2020-01-01'
STOP_TIME = '2029-12-31'
STEP_SIZE = '1 d'
REF_SYSTEM = 'J2000'
OUT_UNITS = 'KM-S'
VEC_TABLE = '2'
CSV_FORMAT= 'YES'
```

The main advantage of the language *perl* is its simplicity when it has to modifies and create texts and its use of strings variable. Therefore, just from a txt file that contains the desired batch of asteroids's designation, *perl* can modify the request format into the url that will be used to access the ephemeris. This url is compossed of an initial fixed script `https://ssd.jpl.nasa.gov/horizons_batch.cgi?batch=1` followed by the arguments that defined the NEAs search concatenated by "&". In addition, some characters has to be transformed from plain text form into HTML code, just to make the url able to interpret them. For example, blank space characters inside NEAs designation has to be converted into `%20`, obtaining `'1898%20DQ'` from `'1898 DQ'`. The preamble of the email's standar, `!$$SOF` is not used in the final url. The transciption of the request used before as example would give the following url:

```
https://ssd.jpl.nasa.gov/horizons_batch.cgi?batch=1&COMMAND=%271898%20DQ%27
&MAKE_EPHEM=%27YES%27&TABLE_TYPE=%27VECTORS%27&CENTER=%27500%4010%27
&REF_PLANE=%27ECLIPTIC%27&START_TIME=%272020-01-01%27&STOP_TIME=%272029-12-31
%27&STEP_SIZE=%271%20d%27&RF_SYSTEM=%27ICRF%27&OUT_UNITS=%27KM-S%27
&VEC_TABLE=%272%27&CSV_FORMAT=%27YES%27
```

At this point, the interface is able to create the url for the request. Nevertheless, *perl* counts with LWP[6], a CPAN[7] API that make `http` protocol communitacions posible. Therefore, the application developed is able not just to create the request address but also to use it to read the output data. As the information obtained through this method is a plain text that follows an standard format, *perl* can be used to modify it an create csv files that MATLAB finds easy to read. Eros' example, the information that *perl* reads is shown in Appendix A.

The output displayed shows first some information about the request, like date and hour when it has be done, the required body's name and physical data about it or epoch references. Followed by this and introduced by a bunch of asterisk, a table with dates, positions and velocities. Only first row of ephemeris has been introduced in the previous example for clarification. Notice that

[6]http://search.cpan.org/dist/libwww-perl/lib/LWP.pm
[7]http://search.cpan.org/faq.html

both position and velocity are given in cartesian coordinates as was specified in the previous request with the argument `VEC_TABLE = '2'`. What is going to be useful to *perl* is the fact that data is introduced by preamble `$$SOE` and endend by `$$EOE`, being perfect breakpoints that indicates which information has to be extracted.

```
$$SOE
2458849.500000000, A.D. 2020-Jan-01 00:00:00.0000,  1.618400496950530E+08, -2.1
17639824256859E+08,  2.748215348887712E+06,  1.507944235344202E+01,  1.21014960
1668715E+01,  3.687729358116847E+00
...
...
...
$$EOE
```

Finally, ephemeris can be obtained and imported into a csv file, as the information is given in this format already due to the command `CSV_FORMAT = 'YES'`. Output would be an eight columns file, being: Julian Date, Calendar Date (Barycentric Dynamical Time), X coordinate, Y coordinate, Z coordinate, X velocity component, Y velocity component and Z velocity component.

Thanks to *perl* language, a NASA HORYZONS Systems databe-MATLAB interface have been developed which, using IAU's Nomenclature, can provided a high number of asteroid's ephemeris ready to be used in MATLAB and SPICE JPL API.

3.2 Lambert's Problem

The astrodynamical problem known as "Lambert's Problem" is the one in which two vectors positions and the transfer time among them are known. The trouble is that neither the orbit between the initial and the final location nor the velocities at each points are not known. The solution to this gives not only a feasible orbit but the one that ensures a minimun transfer ΔV, however there are other parameters that have to be given in order to close entirely the problem.

The orbital plane is defined just from the start of the problem, and the optimum trajetory for the required time will lay in this plane. Even so, there are two possible solutions for the same orbit, which are the one of taking the "long way" or the "short" one to arrive at final position. This dilemma is ilustrated in Figure 3.1. The path to be taken, the transfer method t_m, can be specified and the solution can be forced to follow one of the directions. t_m can take value $+1$ or -1 as function of the true anomaly difference of position vectors, Equation 3.1, being positive for angles lower than 180° and negative for higher values of the angle. In this way, the sine may be forced to have a determined signed just by multiplying it by t_m, Equation 3.2.

$$cos\left(\Delta\nu\right) = \frac{|\vec{r_0} \times \vec{r}|}{\vec{r_0} \cdot \vec{r}} \tag{3.1}$$

$$sin\left(\Delta\nu\right) = t_m\sqrt{1 - cos^2\left(\Delta\nu\right)} \tag{3.2}$$

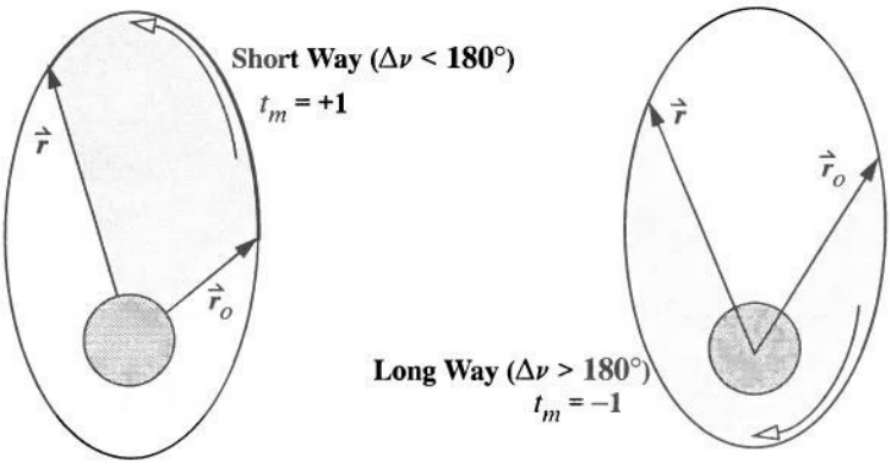

Figure 3.1: Transfer Methods

The only remains that left to close the problem is the number of revolutions that precedes to endpoint definitive arrival. However, this has been simplified to the arc in the transfer orbit between points and no extra revolution is done, as it would just lead to an increase in time with no benefit for the total Δv.

Lambert's Problem has been used in all the four analysis that have been done through this work. In the two cases in which a direct transfer orbit Earth-Asteroid has been considered the initial position was the Earth's one at a determined departure time t_{dep} while, in the other hand, the final position was that of the Asteroid's one at a defined arrival time t_{arr}. The transfer time, or Time of Flight TOF, is directly derived from the two previous times $TOF = t_{arr} - t_{dep}$. The position of each body at a certain time is known thanks to the *perl* interface developed, explained in the previous section. Although dates are given by the interface in Julian and UTC standars through the code ephemeris times, "*et*", are used, going from the firsts to *et* using SPICE Toolkit.

The problem of matter was first solve in 1971 by the french mathemathician Johann Heinrich Lambert and since then several methods have been found in order to solve it. The approach taken in this work is the Universal Variables Method, propossed by Battin in 1987 and used by Vallados [38], who obtaind these variables through a bisection Newton-Raphson's method. Universal Variables χ_0, y and ψ are contained in function series f and g, Equation 3.3, which are defined in Kepler's Problem, Equation 3.4,:

$$\begin{aligned} f &= 1 - \frac{\chi_0^2}{r_0} c_2 & g &= t - \frac{\chi_0^3}{\sqrt{\mu}} \\ \dot{f} &= \frac{\sqrt{\chi}}{r r_0} \chi_0 \left(\psi c_3 - 1\right) & \dot{g} &= 1 - \frac{\chi_0^2}{c_2} \end{aligned} \tag{3.3}$$

$$\begin{aligned} \vec{r} &= f\vec{r_0} + g\vec{v_0} \\ \vec{v} &= \dot{f}\vec{r_0} + \dot{g}\vec{v_0} \end{aligned} \tag{3.4}$$

At this point, the first case of study can be solved and analyzed. As it introduced before, the approach taken in this case is a direct inspection of each possible transfer orbit in the desired range time which, for all analysis, is going to be from 01/01/2020 to 31/12/2029 in departure times. Maximum arrival times are going to be given in this first proposal as functions of the orbital period, being the final date the addition of the initial one plus this period. Therefore, Lambert's Problem is going to be analysed for each date and within this date with all possible arrival positions in an orbital period, ensuring any combination of Earth-Asteroid relative positions. Finally, the minimum Δv can be found among all solutions and porkchop plots can be developed, with Δv for each t_{dep} against TOF.

3.3 Nondominated Sorting Genetic Algorithm II. NSGA-II.

Genetic Algorithms (GAs) were first introduced by John Holland in the 1960s [39] in its studies about natural adaption mechanisms reproduced by computer systems. The idea that Holland developed in its works is based in the evolution of an initial population into a "better" group of individuals through "natural selection". Each individual is called a "gen", the set of all of them is the "chromosome" and each iteration of the genes and the birth of new ones is a "generation". Therefore, through this natural selection process, the initial chromosome recombines with other set of genes, giving as result a third group of solutions that are evaluated. This evaluation determines which genes are better or fit better into the solution and which ones should be disregarded.

GAs have been employed in this work to optimize time of flights and ΔV in the transfer trajectories, as these kind of algorithms allow multi-objective optimization. The final result of these algorithms gives a Pareto-Optimal Front with the last generation of the chromosome, which has the best genes. The GA that have been use to solve the multi-objetive optimization problem is the Nondominated Sorting Genetic Algorithm II (NSGA-II), due to its elitism and its nondominated sorting approach [40].

NSGA-II can be splited in a serie of processes and functions. The first of them is the initialization of the "N" population of genes, based in the range and in the constrains that have been determined at first. All the individuals that are generated are then used to solve the problem of matter and, after this, each gen is sorted in a nondominated way. The meaning of this is that each of the solution generated by the "N" initial gens is evaluated as a function of, not only its performance, but of the entire chromosome. The performance is measured with the objectives variables, which are the results to be optimized. As the problem is a multiobjetive one, there would be a set of solutions that would behave better according to some objective variables but worst according to others, therefore the result of this sorting method is a set of gens whose variables can not be changed without making worse the other ones. In the case of direct transfer orbit, for example, these objective variables are the Time of Flight and the ΔV, therefore solutions with the best performance would be those that for their TOF no better ΔV is found. This set, with the "best solutions" to the problem, is called a "front", an inside it there is no better or worst solutions, no one dominates about the others. The total "N" solutions are then sorted in different non-dominated fronts, each one with a determined performance of the problem. In addition to this process, a crowding distance is also asigned. This distance just measures the geometrical space between solutions, giving priority to separate solutions than to close ones, resulting in a more representative set of results. Otherwise, the algorithm may just focus in a small region of space, obliterating other possible results [41].

After initialization, evaluation and nondominated sorting, it is time to propagate better solutions above the whole populationn, by means of genetic operators SBX (Simulated Binary Crossover) and polynomial mutation [41] [40]. The basic idea of these operatos is that a set of parents, which are selected from the best results of the previous evaluation, gives a set of new gens. These new childs will be a recombination of parents' solutions. Nevertheless, some "mutations" of the previous genes have to be introduced in order to avoid similar solutions to propagate in excess, to stop acumulative inbreeding. Finally, a new set of "N" genes are borned from the previous population.

The next step in NSGA-II is the recombination of the two populations, the initial one and the new one. This recombination is just another nondominated sorting evaluation, like the one done to the initial population. From the total $2N$ genes, a new generation chromosome of "N" genes is obtained as result of the recombination of the best ones of the previous populations. This is called elitism, as the new results are compared to the old ones, and only the ones with better performance are selected. Propagation to the next generation is done only from the best solutions among parents and childs.

Finally, recombination would give an "N" gen chromosome, a new generation. This process would iterate through an specific number of generations, giving birth to new solutions and choosing only the ones with better perfomance. The final result of NSGA-II would be the best front of genes that have been generated throught this evolution process.

The second case of study of this work is the resolution of Lambert's Problem by means of NSGA-II. The constrains and limits are settled through a total of two decision variable, which refer to departure and arrival times. The first time is obtained from ephemeris, going from 01/01/2020 to 31/12/2029, as in the first case. The range of arrival times follows the same rule than the ones from the previous study case, being the lowest one the departure date plus 10 days and the maximum one the departure plus the Asteoird period. The objectives variables to be evaluated are the Time of Flight and the ΔV, as introduced before as an example. Another constrain has been introduced in the generation of childs and their mutation, forcing the decision variable of the departure time to be lower than the one of the arrival time, avoiding therefore unnecesary analysis of genes like this.

3.4 Method of Patched Conics. Flyby Transfer.

Gravity Assists or flybys have been modelled according to the Method of Patched Conics. This approach asumes that in a three bodies problem, within a certain region of the space called "Sphere of Influence" (SOI), the trajectory of the body of interest is driven only by the smallest one of the others two. For a NEA's transfer trajectory, which has an Earth flyby, when it approach the encounter it enters the Earth's SOI and therefore Sun's gravity can be neglected. Therefore, the whole transfer can be divided into a first orbit departing from Earth and arriving to it again at the flyby date and a second orbit that goes from Earth at the flyby date and reaching the NEA at the arrival time. Both transfers or legs would be joint by the flyby, which is modelled by Patched Conics.

$$r_{SOI} = a\left(\frac{m}{M}\right)^{2/5} \tag{3.5}$$

The conditions specified for flyby to occur are the following:

$$\vec{x}\left(t_{fb-}\right) = \vec{x}_E\left(t_{fb-}\right) \tag{3.6}$$

$$\vec{x}\left(t_{fb+}\right) = \vec{x}_E\left(t_{fb+}\right) \tag{3.7}$$

$$\vec{x}\left(t_{fb+}\right) = \vec{x}\left(t_{fb-}\right) \tag{3.8}$$

$$\vec{v}_{\infty fb-} = \vec{v}\left(t_{fb-}\right) - \vec{v}_E\left(t_{fb-}\right) \tag{3.9}$$

$$\vec{v}_{\infty fb+} = \vec{v}\left(t_{fb+}\right) - \vec{v}_E\left(t_{fb+}\right) \tag{3.10}$$

$$|\vec{v}_{fb+}| = |\vec{v}_{fb-}| = |\vec{v}_{\infty}| \tag{3.11}$$

$$\vec{v}_{\infty fb+} \cdot \vec{v}_{\infty fb-} = v_{\infty}^2 cos(\delta_t) \tag{3.12}$$

$$sin(\delta_t/2) = \frac{\mu_E/\left(R_E + h_{pE}\right)}{v_{\infty}^2 + \mu_E/\left(R_E + h_{pE}\right)} \tag{3.13}$$

$()_{fb}$:	Related to flyby	$()_{fb+}$:	Immediately after flyby
$()_{fb-}$:	Immediately before flyby	$()_E$:	Related to Earth
t:	Time $[s]$	$\vec{x}$:	Position vector in cartesian coordinates $[km]$
$\vec{v}$:	Velocity vector in cartesian coordinates $[km/s]$	$\vec{v}_{\infty}$:	Hyperbolic excess velocity vector $[km/s]$
δ_t:	Flyby turn angle $[-]$	μ:	Gravitational parameter $[km^3/s^2]$
R:	Body radius $[km]$	h_p:	Height with respect to the surface at flyby periapsis $[km]$

The first three conditions, Equations 3.6 - 3.8, state that positions at flyby and also inmmediately before and after it of both Earth and transfer orbit has to be equal, meaning that it can not be discontinuities between both legs. Condition 3.9 establish that the hyperbolic velocity prior to the encounter has to be the difference between the velocity with respect to the Sun and the Earth orbital velocity at that moment. In the other hand, condition 3.10 is the same condition than 3.9 but just after the gravity assist. As no impulsive maneuver is going to be considered in the flyby, total energy has to be conserved and therefore orbital speed before and after the encounter has to be also conserved, as condition 3.11 says. Equation 3.12 and 3.13 define the angle between orbital velocities at the beginning and at the end of the maneuver and the height above Earth surface at which it would be realized.

The constrains that are going to close this approach are the next ones:

$$t_{G+} = t_{G-} \tag{3.14}$$

$$h_{pM} \geq 50km \tag{3.15}$$

$$v_{\infty} \geq 0.25km/s \tag{3.16}$$

However, in order to have lower computational load, tolerances in condition 3.10 have been relaxed to:

$$|\vec{v}_{\infty G+}| - |\vec{v}_{\infty G-}| \leq 1m/s \tag{3.17}$$

The way in which this model is employed in this work is by assuming a departure, flyby and arrival time and obtaining Lambert solutions to leg Earth-Earth and to Earth-Asteroid. Results from the first transfer would give departure velocity from Earth and $\vec{v}\,(t_{fb-})$ and from the second one, arrival velocities and $\vec{v}\,(t_{fb-})$. As both Earth orbital velocities, $\vec{v}_E\,(t_{fb-})$ and $\vec{v}_E\,(t_{fb+})$, are known from ephemeris, condition 3.11 and constrain 3.16 can be studied. If both are fulfilled, then the turn angle δ_t can be computed from condition 3.12 and with it flyby altitude, h_{pE}, would be obtained from condition 3.13. Finally, the assumed flyby would be a feasible one if constrain 3.15 is also fulfilled. Therefore, Lambert Problem is solve for a combination of departure, flyby and arrival dates in which flyby conditions are iterate with fixed departure and arrival times. Once the full flyby spectrum is analysed for that conditions, a new approaching date is given and the process is repeated through all arrival times, giving after that a new departure time and starting a new iteration. All conditions are analysed, giving a set of possible conjunctions of dates in which flybys are assured.

This method is the one used for the third case of study, taking as departure dates the same as before. However, arrival times have to be considered to be higher, as one penalty that flyby introduces is the increase of Time of Flight. In this case, TOF of the first leg have been limited to go from one hundred days to three years, considering total TOF up to five years. The fourth case of study follows the same procedure, but it uses NSGA-II to iterate and evolve results. The GA works as in the second case but a new decission variable has to be introduced, the arrival time and the function to be evaluated is the two Lambert Problem approach.

3.5 Analysis

As it has been introduce through previous sections, the analysis of the optimization of NEAs transfer orbit have being done in four different cases of study. In each one, a different approach has been taken, optimizing different parameters of the problem, like ΔV needed to stablish an orbit, TOF of the trajectory and computational optimization.

3.5.1 Transfer through straight Lambert Problem's Resolution

This approach simply takes the ephemeris and use its information to solve Lambert's Problem through the whole spectra of departure epochs. It takes an specific launch time and over it, it iterates Lambert's Solution through the range of arrival times, which goes from ten days from departure up to a whole asteroid period. Each departure and arrival iteration and their solution are perfomed with a time step of a day. Results obtained through Lambert's evaluation over the entire epoch are porkchop plots of departure Δv_{dep}, arrival Δv_{arr} and total Δv_{total} and, for the minimum Δv condition, TOF, epochs of departure and arrival, a 3D trajectory plot and its projection into the Ecliptic Plane.

$$\begin{gathered}
t_{dep,0} \equiv 01 - 01 - 2020 \quad t_{dep,N} \equiv 31 - 12 - 2029 \\
t_{arr,0,i} = t_{dep,i} + 10 \ [days] \quad t_{arr,N,i} = t_{dep,i} + T_{NEA} \\
t_{dep,j+1,i} = t_{dep,j,i} + \Delta t \quad t_{arr,i+1} = t_{arr,i} + \Delta t \\
\Delta t = 1 \ [day]
\end{gathered} \tag{3.18}$$

3.5.2 Lambert's Problem solved using NSGA-II

The second case of study is the optimization of the previous approach by means of using NSGA-II. As explained before in Section 3.3, the decision variables and their range along with the objectives ones have to be defined also with boundaries and constrains. A total of two decision variables has been set into this analysis, the departure time and the arrival one, and the range have been maintained as in the first case. However, in this case the inputs are generated in a random manner, so inside the genetics operatos a constrain have been defined: $t_{dep} < t_{arr}$. Two objectives variables are going to be optimized, being them Total time of Flight and ΔV, giving as result the Optimized Pareto Front of this variables. A population of 100 genes have been used through a total of 100 generations.

$$\begin{gathered}
t_{dep,min} \equiv 01 - 01 - 2020 \quad t_{dep,max} \equiv 31 - 12 - 2029 \\
t_{arr,min} = t_{dep} + 10 \ [days] \quad t_{arr,max} = t_{dep} + T_{NEA} \\
N_{generations} = 100 \quad N_{population} = 100
\end{gathered} \tag{3.19}$$

3.5.3 Flyby transfer through straight Lambert Problem's Resolution

Taking the same approach that the first case, this is a direct approximation to the Flyby problem. As said before, two legs are defined being the first one a transfer Earth-Earth and the second one an Earth-Asteroid orbit. Three dates are going to be considered now, the departure one, the flyby one and the arrival one, with their respectives ephemeris positions and velocities. The process is the same, fixing departures and arrivals and iterating over these conditions the flyby dates, looking therefore for the ones that fulfil the constrains. Combination of dates whose results fulfil the conditions will be considered feasible gravity assist, which were explained in Section 3.4. The outputs obtained are two plots of the 3D trajectory and its projection into the Ecliptic Plane and the minimum Δv with the dates at which it may occurs.

$$\begin{gathered}
t_{dep,0} \equiv 01-01-2020 \quad t_{dep,N} \equiv 31-12-2029 \\
t_{arr,0,i} = t_{dep,i} + 150 \; [days] \quad t_{arr,N,i} = t_{dep,i} + 5 \; [years] \\
t_{fb,0,j,i} = t_{dep,i} + 100 \; [days] \quad t_{fb,N,j,i} = t_{dep,i} + 3 \; [years] \\
\Delta t = 15 \; [day] \quad t_{arr,i+1} = t_{arr,i} + \Delta t \\
t_{dep,j+1,i} = t_{dep,j,i} + \Delta t \quad t_{fb,k+1,j,i} = t_{fb,k,j,i} + \Delta t
\end{gathered} \tag{3.20}$$

3.5.4 Flyby transfer solved by means of NSGA-II

In the last case, the flyby transfer is analyzed again but it is solved using NSGA-II to, again, optimize it. Flyby time has to be added to the decision variables that were used in the second case and its range has to be defined. Evaluation function would deal now with both transfer legs and with the constrains of the Patched Conics. The result is therefore a Pareto Front with the optimized genes, each one with the three dates and the conditions of the trajectory. Same population than in the second study have been used but generations haven been increased up to 200. Within the genetics operators function an additional constrain, associated with flyby epoch, has been introduced, just to assure that random generation does not give flyby times neither bigger than arrival ones nor smaller than the departure.

$$\begin{gathered}
t_{dep,min} \equiv 01-01-2020 \quad t_{dep,max} \equiv 31-12-2029 \\
t_{arr,min} = t_{dep} + 150 \; [days] \quad t_{arr,max} = t_{dep} + 5 \; [years] \\
t_{fb,min} = t_{dep} + 100 \; [days] \quad t_{fb,max} = t_{dep} + 3 \; [years] \\
N_{generations} = 200 \quad N_{population} = 100
\end{gathered} \tag{3.21}$$

Chapter 4

Results and conclusions

To strive, to seek, to find, and not to yield

Lord Tennyson

Previous sections tried to give first a global context about asteroid mining projects and a basis of the fields and troubles that should be considered. The "leitmotif" of the work is, however, NEA's accesibility and energy cost in terms of Δv of their transfer trajectories, which is one of the preceding parameters. As mentioned in Section 3.5, a total of four different analysis have been done, being each one performed through different methods, whose results are introduced in its respective section inside this chapter. Each one of them, would be accompanied with a discrete description of the results obtained, conclusions of the proper analysis and computational times. After this, global conclusions would be introduce, ending with future works and possible extensions of this work.

Transfer trajectories and porkchop plots are shown in Apendix just for clarification.

4.1 First case of study results: Transfer through straight Lambert's Problem Resolution

The first of the analysis perfomed, introduced in Section 3.5.1, have been the direct transfer and its resolution by an straightforward Lambert's Problem solution. That was looking for the most optimum Earh-NEA orbit through each departure date in the selected period and by conditions shown in Equations 3.18. Transfer velocities, dates and time of flights obtained through this analysis are presented in Table 4.1.

NEA	Δv_{Total}	Δv_{Dep}	Δv_{Arr}	Departure Date	Arrival Date	Time of Flight [$days$]
433 Eros (1898 DQ)	7.2769	1.3917	5.8852	17/07/2025	21/02/2026	219
66391 (1999 KW4)	21.2556	10.6205	10.9156	06/06/2020	03/12/2020	180
185851 (2000 DP107)	8.5578	4.0001	4.4240	28/06/2024	11/10/2025	470
494658 (2000 UG11)	10.1317	6.5230	3.6740	13/01/2025	23/07/2025	191
459872(2014 EK24)	3.4484	2.5798	0.8686	11/07/2020	10/08/2021	330
— (2014 SC324)	7.4354	6.6763	0.7591	29/11/2022	25/12/2024	757
162173 Ryugu (1999 JU3)	4.3545	2.8717	1.4828	24/12/2020	03/06/2021	161
253062 (2002 TC70)	4.3166	1.7579	2.5586	15/09/2028	19/08/2029	338
— (2011 CG2)	3.5851	1.9874	1.5976	08/05/2020	18/04/2021	345
— (2001 QC34)	4.6086	2.3340	2.3208	27/02/2020	23/06/2020	148
— (2013 PA7)	3.0704	1.3606	1.8181	11/01/2029	31/10/2029	293
— (2008 HU4)	1.1284	0.8188	0.5431	26/05/2026	07/05/2027	366

Table 4.1: First case of study results

Eros, the first NEA from the list of twelve, shows a Δv_{total} of 7.2769 [km/s] in its most optimum transfer trajectory. The injection to this orbit from Earth, would be performed at the departure date of the seventeenth of may of 2025, with an scape cost of Δv_{dep} of 1.3917 [km/s]. Total time of flight would be 219 days, arriving at 21/02/2026, with a rendezvous cost of 5.8852 [km/s].

In the other hand, 1999 KW_4 Δv_{total} is of 21.2556 [km/s], being the highest Δv of all the results of this analysis. This value is almost equally share between arrival Δv and the departure one, while in the previous NEA from the total of 7.2768 [km/s], 5.8552 [km/s] were due to the arrival. This fact may be due to the change in inclination of the orbit, which is perfomed mostly in the second burn of the trajectory of the first case while in the second in divided in both of the impulsives maneuvers. Although, according what have been shown in Table 2.5, 1999 KW_4 may looks like a closer orbit to Earth, having an aphelion of almost 1 [AU] ,than the one of Eros, the higher inclination of 1999 KW_4, with 38.88°, makes this asteroid a more expensive one and less accesible. This result makes sense with what was explain in Section 2.2, where inclination was introduced as one of the parameters whose influence was bigger. Inclination's impact in total Δv can be also observed in 1999 JU_3 and 2001 CG_2 results, as both have similar semi-major axis (1.1895 [AU] and 1.1774 [AU]), eccentricities (0.1903 and 0.1585) and perihelions (0.9632 [AU] and 0.9907 [AU]) while having the first one a Δv_{total} of 4.3545 [km/s] against the 3.5851 [km/s] of the second one. The main difference between Ryugu (1999 JU_3) and 2011 CG_2 is the inclination, being 5.8839° for the first NEA and 2.7571° for the second one.

Looking at other orbital elements, 2000 DP_{107} shows a Δv_{total} of 8.5578 [km/s], which is bigger than the 7.2769 [km/s] of Eros. In this case, inclination is half the value of Eros' one, however 2000 DP_{107} has an orbit which is farther and whose eccentricity is also higher, making its less circular. Results for 2000 UG_{11}, which has a high eccentricity (0.5725), shows a Δv_{total} of 10.1317 [km/s] with a semi-major axis 0.6 [AU] above 2000 DP_{107} one. In fact, the only NEA results that left whose cost is above 5 [km/s] is 2014 $_{324}$, which with a semi-major axis of 1.921 [AU], a high eccentricity of 0.5250 and an inclination of 1.6539° has a $\Delta vtotal$ of

7.4355 $[km/s]$.

A link between orbital parameters and energetic cost can be found in the results that are given by this analysis. Similar orbits would lead to similar costs, as 2011 CG_2 and 2014 EK_{24} results show, having both of them low values in their semi-major axis and low eccentricity and inclination. Although 2011 CG_2 has lower inclination, 4.8041° against 2.7571°, it has a less circular orbit, being its e 2.814 times bigger, and a Δv_{total} only $0,1367$ $[km/s]$ larger. This, again, shows that i has a bigger effect but that the eccentricity also takes its part in transfer's cost. A NEA whose Δv is similar to these two is 2013 PA_7, with a total of 3.0704 $[km/s]$. PA_7 has a similar orbit to 2014 EK_{24}, as both eccentricities are similar and semi-major axis are near 1 $[AU]$, however its inclination is 1.3304° lower, reducing its cost.

Ryugu and 2002_{70} have cost around 4.3 $[km/s]$, being 4.3560 $[km/s]$ and 4.3887 $[km/s]$ respectively. This case give some insight about the relation of the inclination against the semi-major axis, as eccentricity is similar for both of them, 0.1903 and 0.1967. Ryugu's orbital plane is at 5.8839° and 2002 TC_{70} at 2.1740°, however, a are 1.1895 $[AU]$ and 1.639 $[AU]$ making 1999 JU_3 orbit closer than the other one. 2001 QC_{34} is similar both in results and orbit to Ryugu, being $0,2541$ $[km/s]$ more expensive due, again, to the higher inclination angle.

The main conclussion that these results exhibit, is that less circular orbits at higher inclination angles would lead to higher energetic cost. In the other hand, NEAs with a lower eccentricity, lower i and closer to Earth's orbit would be desired when looking for asteroid mining trajectories. One example of this conclusion, is 2008 HU_4, which has a total Δv of 1.1284 $[km/s]$, being the lower value but also the less eccentric orbit and the one whose orbital plane is close to the one of the Ecliptic.

Porkchorp plots, which are shown in Appendix C.1, show Δv that would be required to reach a NEA at different departure dates and time of flights. They useful, therefore, to estimate dates at which it would be more efficient to launch the "mining probe" and how long it would take until the arrival. However, NEA orbital parameters have their influence in the final results that is given in these plots. One of the clearer influences is that of the Synodic Period, T_{syn}, introduced in Equation 2.1 in Section 2.2. In Figure C.1, which is Eros' Porkchop Plot, a region of low Δv appears at a TOF of 400 $[days]$, showing again after a bit more of 2 years, same period as the synodic one. 1999 KW_4, Figure C.2 , shows similar "bubbles" after one year, similar again to the synodic period, 2000 DP_{107}, Figure C.3 after two years and a half, and so on. 2014 EK_{24}, Figure C.5, and 2008 HU_4, Figure C.12 may look different, but it has to be considered that theri T_{syn} is greater that the epoch studied.

Another orbital parameter that can be noticed easily in porkchop plots is the eccentricity. Regions with low Δv can be spotted to repeat at a given angle, an inclination that is going to be more horizontal for near circular orbits than for more elliptical ones. Just taking a look to 2014 SC_{324}, Figure C.5, and 2008 HU_4, Figure C.12, this near horizontal angle can be noticed, increasing in NEAs like 2000 UG_{11}, C.4, and 2014 SC_{324}, Figure C.6. Semi-major axis', a, influence can be observed also in these two last porkchop plots, having their NEAs an a close to 1.9 $[AU]$. The similitude, apart from the angle cause by eccentricity, in these two plots is the vertical size of each similar Δv region. In the other hand, orbits with more discrete semi-major

NEA	Δv_{Total}	Δv_{Dep}	Δv_{Arr}	Departure Date	Arrival Date	Time of Flight $[days]$
433 Eros (1898 DQ)	7.3503	1.2837	6.0666	03/07/2025	23/02/2026	235
66391 (1999 KW4)	21.6702	9.0975	12.5727	14/06/2020	06/12/2020	175
185851 (2000 DP107)	8.5932	4.0999	4.4933	23/06/2024	11/10/2025	475
494658 (2000 UG11)	10.1898	6.7741	3.4157	19/01/2025	28/07/2025	190
459872(2014 EK24)	3.4668	2.5074	0.9594	12/09/2020	18/08/2021	340
— (2014 SC324)	7.4413	6.6541	0.7872	01/12/2022	30/12/2024	760
162173 Ryugu (1999 JU3)	4.3560	2.7954	1.5606	26/12/2020	04/06/2021	160
253062 (2002 TC70)	4.3212	1.7458	2.5754	15/09/2028	21/08/2029	340
— (2011 CG2)	3.6008	2.0466	1.5542	15/05/2020	20/04/2021	340
— (2001 QC34)	4.6153	2.2521	2.3632	31/01/2020	24/06/2020	145
— (2013 PA7)	3.0704	1.4008	1.6696	13/01/2029	04/11/2029	295
— (2008 HU4)	1.1496	0.7614	0.3882	14/05/2026	04/05/2027	355

Table 4.2: 15 days time step results

axis would show smaller region in their vertical length, like 2013 PA_7 or 2001 QC_{34}.

Previous conclussions lead to the thought that circular orbits, which would show a more horizontal pattern of low Δv regions, with small inclination angles, what means lower Δv, are desired. Orbits with high semi-major axis should be avoid, although they give a high range in time of flight it is the horizontal behaviour what is wanted, as it would make possible smaller and faster mining periods. Here also enter the synodic period, but only for some NEAs. Asteroids with a long T_{syn} may seems to be worst to mining frequency, which is going to be true in NEAs like Eros (1898 DQ), Ryugu (1999 JU_3) or 2000 DP_{107}. Asteroids with high eccentricities will see their Δv increase from 9 $[km/s]$ to 30 $[km/s]$, for the case of 2014 SC_{234} (Figure C.6), if departures dates are changed increased only a few months. In more circular orbits, which, as it has been said, give an horizontal behaviour, this variation is going to be lower. 2014 EK_{24} (Figure C.5), with an e of 0.0699, has a vertical region between 200 days and 400 days of Time of Flight in which the only change in cost is from 4 $[km/s]$ to 7 $[km/s]$, being therefore its T_{syn} of 100 years less important.

As it was stated in Section 3.5.1 (Equations 3.18) the maximum arrival date is going to be a function of the NEA orbital period, Table 2.5, a fact that would affect the number of times that Lamber has to be solved. The total amount of iterations, N, would be each departure day through the ten years of the scope times the total number of arrival days. Taking into account that almost all of the twelves NEAs have a period of the same order of magnitude than the Earth's one, this would give a number of iterations of an order of magnitude of one million per asteroid. Finally, the amount of time that this method has taken to calculate its final results is about 3 hours and 50 minutres. It has to be considered the time step of 1 day that has been used, it is not necessary to have such a small Δt. Studying an step of fifteen days, results are given after only six minutes with the results shown in Table 4.2, which are close to the previous one. However, a second iteration could be performed around departure and arrival dates epoch with a time step of 1 day. This method give same results than iteration trough the 10 years with 1 day step, but time is reduced to six minutes of the 15 days iteration and from hour the second one with single day steps.

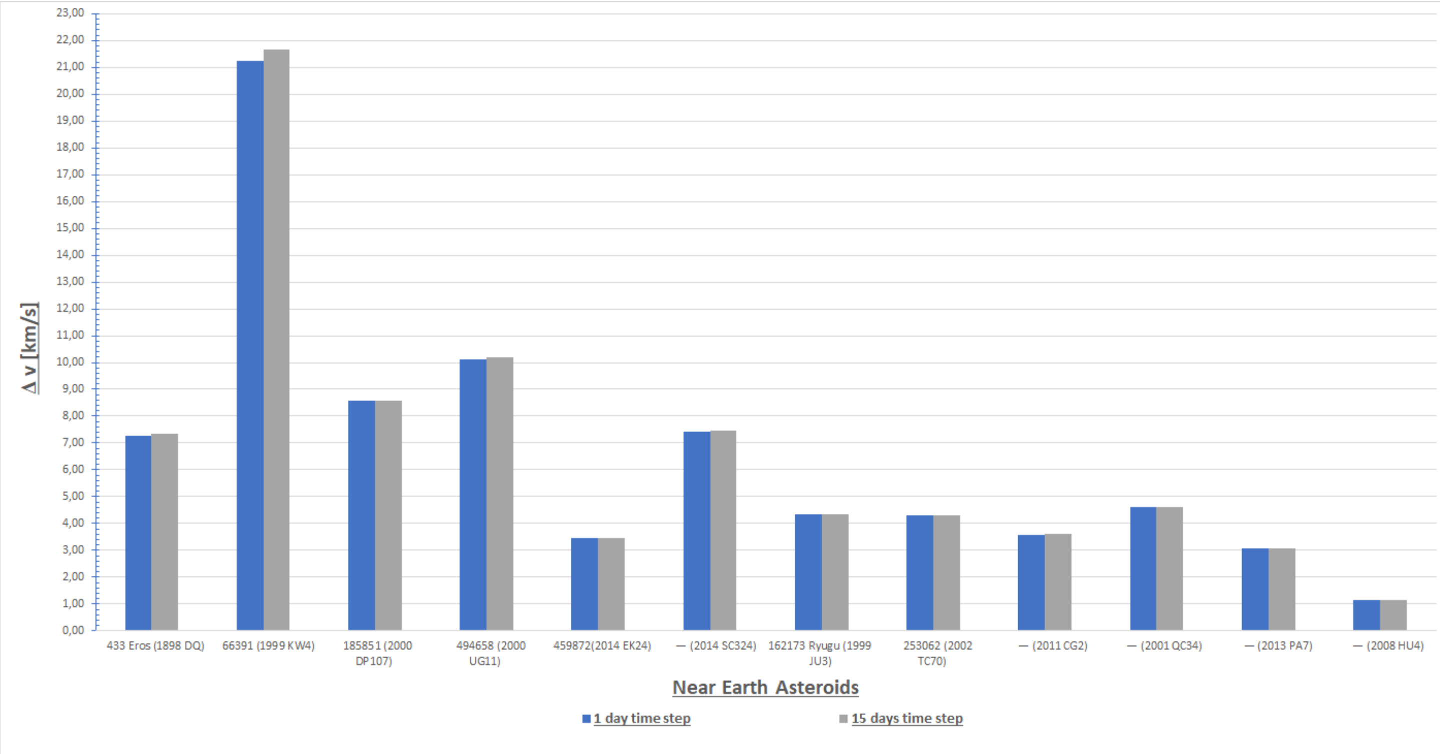

Figure 4.1: Time step variation results

4.2 Second case of study results: Transfer through NSGA-II Lambert's Problem Resolution

The second case of study, which has been explained in Section 3.5.2, takes the same idea of the first one but its approach is through the use of Nondominated Sorting Genetic Algorithm II method. Results of this analysis are presented in Table 4.3, shown next.

From the previous result's table, it may be seen that both Δv and Time of Flight are similar to that presented in Table 4.1. Variations in transfer cost are in any case higher than 0.1 $[km/s]$, which would account as an 11% in the more sensitive case of 2008 Hu_4 $\Delta v_{total} = 1.1298$ $[km/s]$, and having a maximum difference of 0.0721 $[km/s]$. The bigger disparity between both set of results comes with the time of flight of 2002 TC_{70}, being of 338 days for the first analysis and of 165 days for the second one. In fact, the previous difference in Δv mentioned of 0.0721 $[km/S]$ also belongs to this NEA. The reason to this is that NSGA-II has encountered the most optimum transfer orbit in a different epoch than through an straightforward solution, however the energetic efficient presents an small reduction.

It is clear that altough NSGA-II gives results which are generate in a radom way, they are closed enough to the ones obtained through a direct resolution. In fact, transfer orbits are ploted

NEA	Δv_{Total}	Δv_{Dep}	Δv_{Arr}	Departure Date	Arrival Date	Time of Flight [$days$]
433 Eros (1898 DQ)	7.2817	1.5286	5.7531	19/07/2025	21/02/2026	217
66391 (1999 KW4)	21.2878	8.8740	12.4137	11/06/2021	15/12/2021	185
185851 (2000 DP107)	8.5721	4.0589	4.5132	29/06/2024	06/10/2025	464
494658 (2000 UG11)	10.1330	6.5339	3.5991	14/01/2025	22/07/2025	189
459872(2014 EK24)	3.4505	2.5690	0.8815	12/09/2020	09/08/2021	331
— (2014 SC324)	7.4355	6.6802	0.7553	29/11/2022	22/12/2024	754
162173 Ryugu (1999 JU3)	4.3560	2.7954	1.5606	26/12/2020	04/06/2021	160
253062 (2002 TC70)	4.3887	3.6348	0.7538	14/07/2026	26/12/2026	165
— (2011 CG2)	3.5857	1.9958	1.5899	10/05/2020	18/04/2021	343
— (2001 QC34)	4.6102	2.3343	2.2759	28/01/2020	22/06/2020	146
— (2013 PA7)	3.0773	1.3889	1.6884	14/01/2029	01/11/2029	293
— (2008 HU4)	1.1298	0.8207	0.3091	07/05/2026	04/05/2027	366

Table 4.3: Second case of study results

from figure C.13 to figure C.24 for the first case of study and from figure C.25 to C.36 can be compared and they will look almost the same ones. The only difference would be found for 2002 TC_{70}.

This case was solved, as stated in Section 3.5.2, with a population of 100 genes evolved through 100 generations, which took near 3 hours to be solved. With almost the same preccision in its results, NSGA-II takes only the 27% of time than the first method with a time step of 1 day. Reducing both generations and genes to 50, time is also reduces to 50 minutes, being almost all results near to the first ones. Only Eros and 2013 PA_7 show Δv variations that should be taken into account. Results from this last NSGA-II are shown in 4.4

NEA	Δv_{Total}	Δv_{Dep}	Δv_{Arr}	Departure Date	Arrival Date	Time of Flight [$days$]
433 Eros (1898 DQ)	8.4163	6.7687	1.6476	16/01/2028	02/01/2029	352
66391 (1999 KW4)	21.3469	8.8272	12.5197	13/06/2021	14/12/2021	184
185851 (2000 DP107)	8.6069	4.1134	4.4935	30/06/2024	02/10/2025	459
494658 (2000 UG11)	10.1323	6.5460	3.5863	14/01/2025	23/07/2025	190
459872(2014 EK24)	3.4484	2.5798	0.8686	11/09/2020	10/08/2021	333
— (2014 SC324)	7.6101	6.7175	0.8926	08/12/2022	09/10/2023	305
162173 Ryugu (1999 JU3)	5.0159	3.6747	1.3412	24/12/2020	25/03/2021	91
253062 (2002 TC70)	4.3909	3.6294	0.7615	14/07/2026	23/12/2026	162
— (2011 CG2)	3.7595	2.0279	1.7316	20/07/2024	16/05/2025	300
— (2001 QC34)	4.6107	2.3711	2.2396	27/01/2020	21/06/2020	146
— (2013 PA7)	3.5933	1.9661	1.6272	03/01/2024	03/11/2024	305
— (2008 HU4)	1.2349	0.9046	0.3303	11/05/2026	29/03/2027	322

Table 4.4: Second case of study results. $N_{gen} = 50$ $N_{pop} = 50$

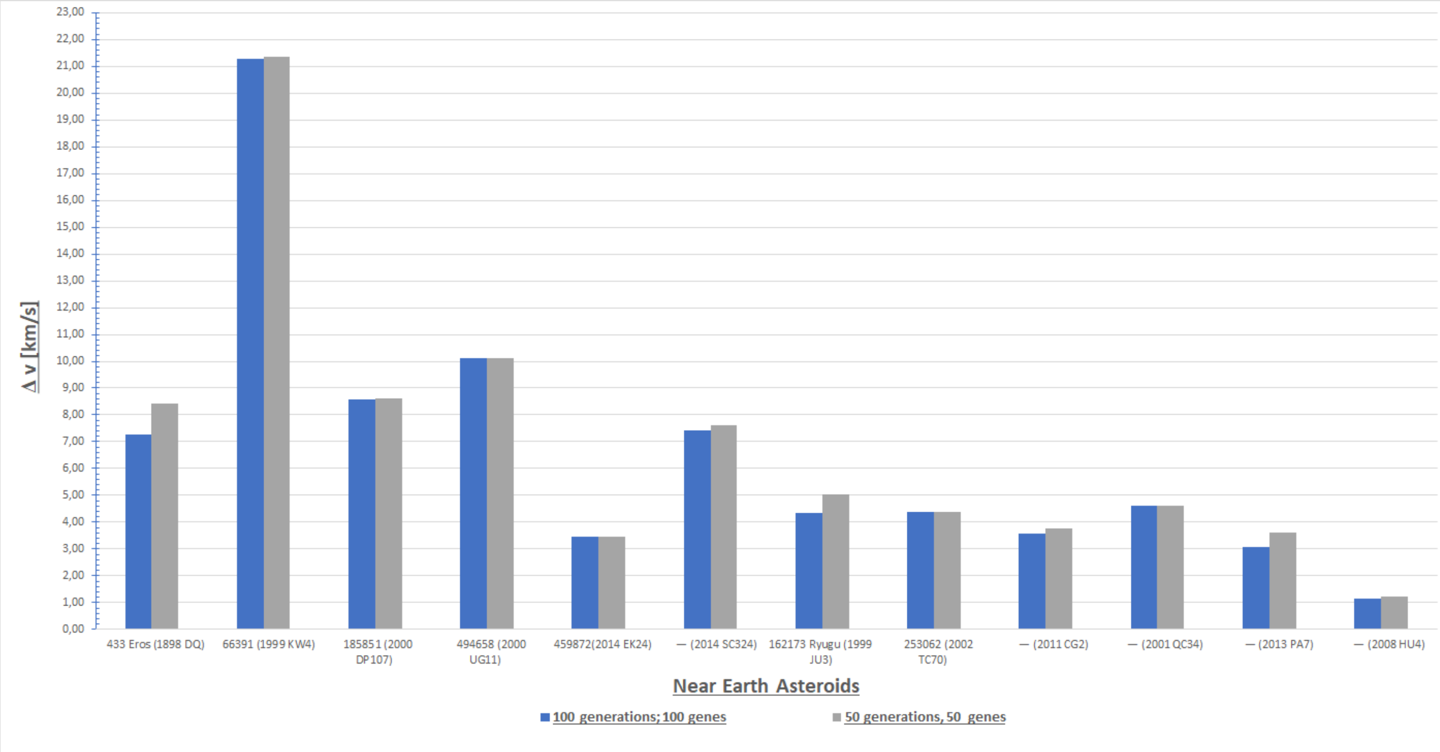

Figure 4.2: Genes population and generations variation

4.3 Third case of study results: Flyby transfer through straight Lambert Problem's Resolution

Among optimization techniques, one of the most used is the method of patched conics. This method have been introduced in Section 3.4 and the first analysis that uses it was explained in Section 3.5.3. Results obtained from this study are presented in the next table:

The main idea of using a Patched Conics Method is that by assuming an increase in time of flight, an optimization in Δv_{total} could be achieved. However, this is not always true or desired. Results obtained from the third analysis, show that for ten of the twelve NEAs the cost is even higher than a direct transfer, being only reduced for 2000 UG_{11} and 2014 SC_{324}. Maximum net gain in Δv is of 0.2366 $[km/s]$, which suppose an increase of a 5.48%, but also an increment of 203 days in time of flight, which would be 26.81%. Variations in results are shown in Table 4.6. Percentages shown in this table have been calculated taking the first set of results as reference, being therefore negative when an lower values are presented in the second set.

Flyby orbits have been considered to occurs from 100 days from departure date to a maximum of 3 years. In the case of 2014 EK_{24}, Ryugu, 2011 CG_2, 2001 QC_{34}, 2013 PA_7 and 2008 HU_4 flyby times have been near or below half a year, while in the other NEAs, the encounter occured after two years. These lower flyby times make the percentage increment of the time of flight lower for the cases whose optimum transfer trajectory are also below or near one year, like 2001 QC_{34} and Ryugu. In the contrary, the ohter asteroids are going to suffer a increment of, at least,

NEA	Δv_{Total}	Δv_{Dep}	Δv_{Arr}	Departure Date	Flyby Date	Arrival Date	Time of Flight $[days]$
433 Eros (1898 DQ)	8.2897	6.5006	1.7891	15/03/2026	19/01/2028	14/12/2028	1005
66391 (1999 KW4)	22.1256	5.3978	16.7277	09/11/2029	15/10/2031	27/04/2032	900
185851 (2000 DP107)	8.9680	5.4015	3.5665	03/07/2025	08/06/2027	29/11/2028	1245
494658 (2000 UG11)	10.0548	6.506225	3.5485	16/03/2023	19/01/2025	18/07/2025	855
459872(2014 EK24)	4.5312	0.7697	3.7615	11/11/2020	10/05/2021	21/03/2022	495
— (2014 SC324)	7.1988	6.5036	0.6952	28/01/2029	04/12/2030	15/09/2031	960
162173 Ryugu (1999 JU3)	5.2920	2.2753	3.0166	07/08/2024	03/02/2025	29/01/2026	540
253062 (2002 TC70)	6.8652	5.4313	1.4339	06/09/2024	12/08/2026	25/11/2026	810
— (2011 CG2)	6.4071	1.0137	5.3934	23/07/2024	19/01/2025	02/08/2025	375
— (2001 QC34)	4.7903	2.3569	2.4334	02/08/2025	29/01/2026	28/06/2026	330
— (2013 PA7)	3.5654	2.1415	1.4239	16/08/2028	12/02/2029	09/11/2029	450
— (2008 HU4)	1.2728	0.9312	0.3416	15/11/2025	14/05/2026	09/04/2027	510

Table 4.5: Third case of study results

NEA	$\Delta v_{Flyby} - \Delta v_{Direct\ transfer}$ $[km/s]$	Δv variation [%]	$TOF_{flyby} - TOF_{Direct\ transfer}$ $[days]$	TOF variation [%]
433 Eros (1898 DQ)	1.0128	13.91 %	786	358.90 %
66391 (1999 KW4)	0.87	4.09 %	720	400 %
185851 (2000 DP107)	0.4102	4.7932 %	775	164.89 %
494658 (2000 UG11)	-0.0769	-0.759 %	664	347.64 %
459872(2014 EK24)	1.0828	31.4 %	165	50 %
— (2014 SC324)	-0.2366	-5.48 %	203	26.816 %
162173 Ryugu (1999 JU3)	0.9375	21.5294 %	379	235.4 %
253062 (2002 TC70)	2.5486	59.041 %	472	139.64 %
— (2011 CG2)	2.822	78.71 %	30	8.69 %
— (2001 QC34)	0.1817	3.94 %	182	122.97 %
— (2013 PA7)	0.495	16.12 %	157	53.58 %
— (2008 HU4)	0.1444	12.79 %	144	39.34 %

Both percentage are given using direct transfer results as reference.

Table 4.6: Variation between direct Lambert results and Flyby results

two years, which is higher than their direct transfer orbits.

In terms of computational time, it has to be noticed that, while in the first case for each departure day a total of $365 \cdot T_{NEA}$ arrival dates were calculated, in this analysis for each departure and arrival dates a total of $3 \cdot 365$ additional iterations have to be performed. This makes that the number of cicles reach an order of magnitude of $7 \cdot 10^9$ and for each one Lambert's Problem is solved twice, checking also if flyby conditions are fulfilled. Taking into account all these factos, is not a surprise that the times taken by the method to be solved increase up to five hours with the time step of 15 days. It has to be noticed that in the first analysis, decreasing the time step increases number of cicles by Δt^2, while in this case it will be increased by a factor of Δt^3.

Results from this analysis show, therefore, that flyby transfers introduce high amounts of time of flight while no decreases are given in Δv or small optimization is achieved. For this reason, direct trajectories would give better performance that Earth gravity assist maneuvers for mining project's missions.

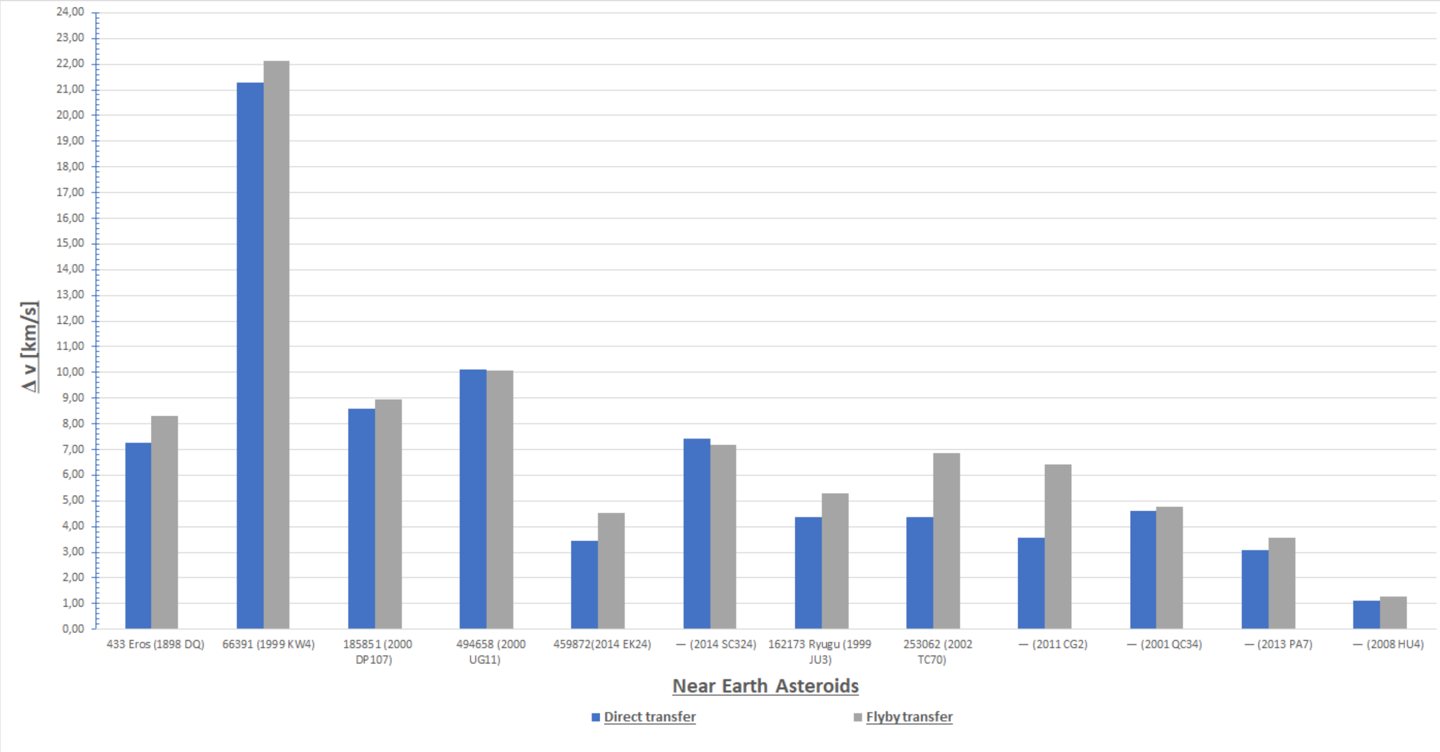

Figure 4.3: Flyby and direct transfer variation

4.4 Fourth case of study results: Flyby transfer solved by means of NSGA-II

Finally, the last case of study, also explained before in Section 3.5.4, solve the flyby transfer problem through a NSGA-II method, given as results the ones that are shown in Table 4.7.

NEA	Δv_{Total}	Δv_{Dep}	Δv_{Arr}	Departure Date	Flyby Date	Arrival Date	Time of Flight $[days]$
433 Eros (1898 DQ)	11.7890	6.8331	4.9559	23/09/2025	24/07/2027	09/02/2028	869
66391 (1999 KW4)	22.4458	6.4478	15.998	22/10/2023	29/08/2025	19/02/2026	851
185851 (2000 DP107)	10.2019	7.3047	2.8972	04/06/2024	12/05/2027	05/10/2028	1584
494658 (2000 UG11)	11.6862	6.2210	5.4652	13/02/2021	25/12/2022	29/10/2024	1354
459872(2014 EK24)	14.9760	4.5465	10.4295	28/03/2024	30/09/2024	01/05/2025	399
— (2014 SC324)	6.1715	5.2441	0.9274	02/01/2026	16/12/2027	10/08/2027	1681
162173 Ryugu (1999 JU3)	7.7105	5.2476	2.04629	25/12/2024	08/12/2026	09/09/2028	1354
253062 (2002 TC70)	10.0028	7.2908	2.7120	09/08/2026	18/07/2029	06/06/2031	1611
— (2011 CG2)	6.4358	5.1897	1.2461	08/03/2027	18/02/2029	05/12/2029	1003
— (2001 QC34)	8.8792	5.2351	3.6441	22/01/2022	02/01/2024	30/11/2025	1408
— (2013 PA7)	8.0704	5.2968	2.7736	11/07/2031	22/06/2033	08/02/2034	943
— (2008 HU4)	10.0244	5.2550	4.7694	28/04/2020	05/04/2022	08/11/2023	1289

Table 4.7: Fourth case of study results

NEA	Δv_{Total}	Δv_{Dep}	Δv_{Arr}	Departure Date	Flyby Date	Arrival Date	Time of Flight [$days$]
433 Eros (1898 DQ)	7.7012	5.1200	2.5812	17/02/2021	27/01/2023	08/02/2024	1086
66391 (1999 KW4)	21.4971	5.9634	15.5337	01/10/2022	21/08/2024	202/02/2025	855
185851 (2000 DP107)	15.7943	5.4145	10.3798	09/10/2021	03/05/2024	21/09/2023	937
494658 (2000 UG11)	10.8119	6.9022	3.9097	17/02/2022	16/12/2023	25/12/2026	1772
459872(2014 EK24)	7.4647	5.0707	2.3940	25/03/2021	06/03/2023	24/02/2024	1066
— (2014 SC324)	6.2385	0.0113	6.2272	18/05/2021	24/02/2022	24/02/2022	568
162173 Ryugu (1999 JU3)	5.8879	5.2239	0.6640	27/12/2027	05/12/2029	12/04/2031	1202
253062 (2002 TC70)	5.8579	0.2752	5.5827	03/07/2022	14/05/2021	18/05/2022	684
— (2011 CG2)	6.1929	5.2982	0.8947	01/08/2027	12/07/2029	21/05/2030	1024
— (2001 QC34)	6.7171	5.2674	1.4497	15/01/2025	08/12/2026	31/03/2028	1171
— (2013 PA7)	7.2623	5.0505	2.2118	14/04/2021	27/03/2023	07/12/2023	967
— (2008 HU4)	0.2905	0.0460	0.2445	18/08/2025	12/04/2026	08/03/2027	567

Table 4.8: Fourth case of study results. $N_{gen} = 300$ $N_{pop} = 100$

As a counter part to the second case's results, Section 4.2, genetic algorithms seems to fail when dealing with the flyby transfer problem, at least with the number of generations and the population stablished in Section 3.5.4. The only NEAs for which NSGA-II gives similar results are 1999 KW_4 and 2000 UG_{11}, what leads to think that more precise solution could be achieved with a higher number of generations. However, this would increase the time that it takes to the code to be executed, which with the present number of genes and generations is around seven hours.

At first it may seems like NSGA-II is far from giving good enough flyby Δv costs, both NSGA-II and direct method should be refine to give results with better precission. The previous method had a time step of 15 days, losing a huge amount of possible flybys that could perform better that the actual ones that it has found. In the other hand, NSGA-II shows case like 1999 KW_4, in which the net difference between the straightforward Lambert resolution and the actual method is of 0.3202 [km/s], but this only means that the genetic algorithm has found a solution which is slightly worse than the other in energetic cost. The epoch in which this solution appears is totally different with the other, having a lower time of flight, being therefore a solution that, altough worse in Δv, its performance in terms of TOF is of better quality. As said before, outputs from this method is not just one solution but a set of solutions than define an optimal front. Maybe after some additional generations, better solutions would be generated in a more optimal front. Results from the Table 4.8 are obtained after 300 hundred generations of a chromosome with 100 genes $N_{generation} = 300$ $N_{population} = 100$. It can be seen that some Δv are lower than the previous solutions, but in their contrary the time of flight have increased. This is telling that altough cheaper solutions are feasible, they come with a price in time, as it can be observed also in Pareto Fronts. However, NSGA-II may give results that their time of flights are better than with 200 generations, as genetic algorithms try to optimize both of them, like in the case of 2000 DP_{107}, whose Δv grows up to 15.7943 [km/s] from 10.2019 [km/s] but its time reduced to 937 days. From this, it can be concluded that a even greater number of generations would be required for some NEAs.

It has been shown that increasing time step in the straighforward Lambert's Problem in the flyby transfer makes computational time to be huge, however increasing generations does

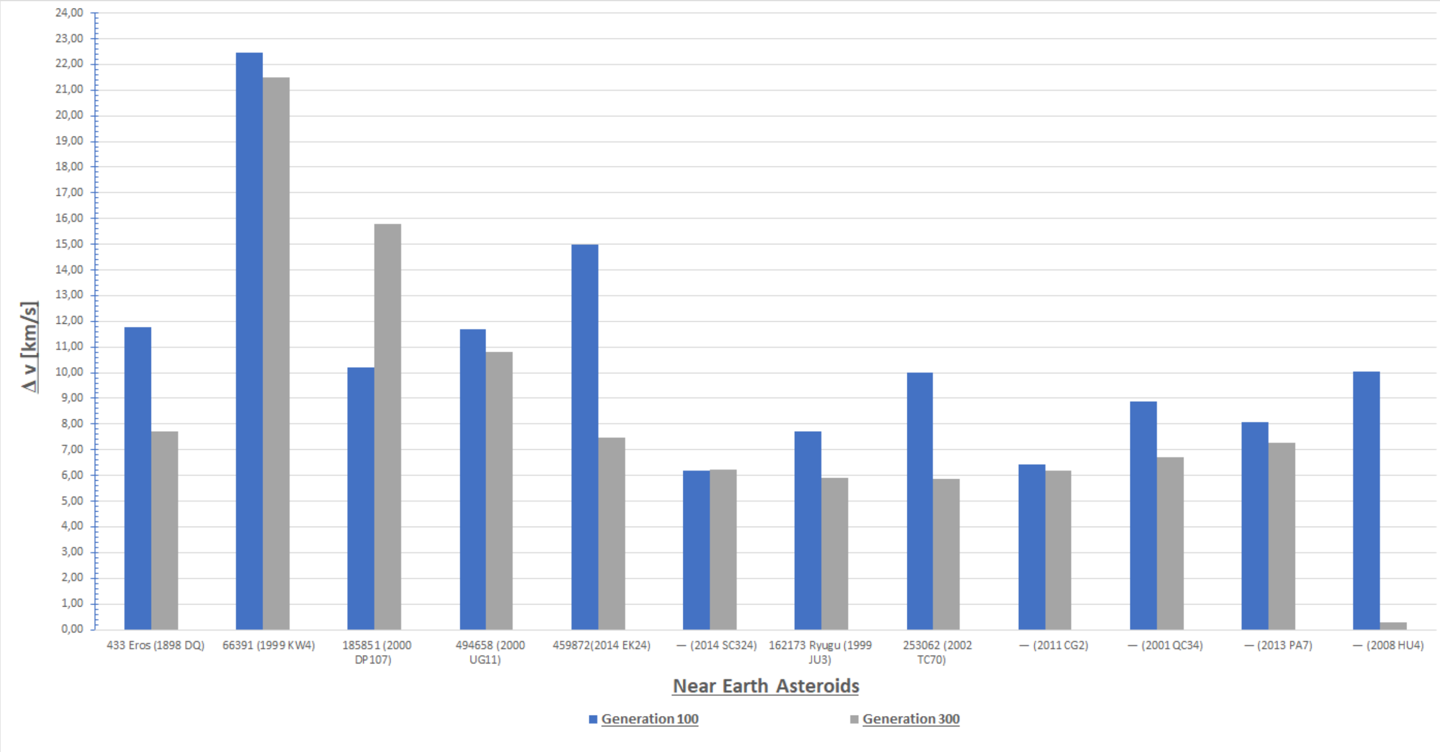

Figure 4.4: Genes population and generations variation

not haves such a negative impact. The first NSGA-II, with $N_{generations} = 200$, takes around seven hours to finish, while the other analysis took around eleven hoyrs and a half. These times are greater than the direct approach, however the preccision of both methods has to be taken into account, and the fact increasing it in the first one would lead to enormeus times. Using a time step of 5 days, instead of the 15 days of the previous one, the direct method took around ten hours to compute just one of the NEAs, Eros, delivering $\Delta v = 7.6807$ $[km/s]$ and $Time\ of\ Flight = 380$ $[days]$. Dates of the previous result would be: $t_{dep} \equiv 03/02/2025$, $t_{flyby} \equiv 07/08/2025$ and $t_{arrival} \equiv 07/08/2025$. This result is better than the one given in Table 4.8 for Eros, as at similar Δv it gives a lower TOF, however it has to be considered that it took almost the same computational time to obtained that one than the others twelve. This last example shows that NSGA-II is faster in solving the Flyby Problem than the direct approach if their precision is increased.

4.5 Final Conclusions and future works

Asteroid Mining is a field that, altough it is not a new idea, has been taking its first steps in recent years. Proper studies and projects are rising nowadays that study this field and try to give an answer to the question that if it would be feasible or economically reliable. Governemt are trying to regulate it and trying to make legal frameworks around it in order to make enterprises able to perform their projects trough legal procesured. However, there is still a long way under these first steps.

This work tried to give some insight about posible transfer trajectories and a way to optimize them through gravity assits. What it has been found is that there is not just one optimum trajectory, as this would be a function both of time and Δv. Of course, there are some orbits that would suit better than others, but in general there should exist a trade off between both parameters.

The Δv_{total} is going to be highly influenced by the parameters that define the orbit of the target NEA. As seen in Section 4.1, NEAs with orbits close to Earth are going to be more desired than NEAs that show difference in their parameters. Between them, the one with a higher influence is the inclination of the orbital plane, being lower the costs of NEAs with small values of it, like 2008 HU_4, than with higher values, like 1999 KW_4. Following to this inclination angle comes the eccentricity. Circular orbits are going to show cheaper energetic costs than others with values close to one. In the other hand, semi-major axis with values near to 1 $[AU]$ would translate into cheaper orbits.

Orbital parameters previously described and their influence in Δv can be studied by means of porkchorp plots. Also in Section 4.1, it has been explained how they are affected by different types of orbit. They allow to find regions with low Δv and the time of flight associated with them, being able to find solutions within this range and not trough the longer time periods. A double iteration process shown in the same Section, 4.1, gave same results than the straighforward method.

The frequency of the mining epochs may be infered from Synodic Periods, Section 2.2, as mention in Section 4.1. Nonetheless, NEAs like 2008 HU_4 see its velocity changed only few so mining would be still cheaper in this “non-optimized” dates than in other NEAs.

Flybys transfer have proved to not be a good option nor in Δv optimization nor in time, altough this one was expected. From the twelves NEAs that have been analysed, only two of them shown a lower cost if a Patched Coninc Method is used to solve the flyby condition, as Figure 4.3. A lower time step may shown better flyby trajectories, but it would computational times. So, maybe a reasonable approach would be to study which of the three dates, arrival, departure or flyby, is more sensitive to changes in δt and use different time steps as functions of this fact. Increasing the number of generations in the NSGA approach show that, although some Δv obtained are better than with $N_{generations} = 200$, in their majority they still give worse results than direct approach. There are only two cases in which flyby gives an energetic optimization, 2014 SC_{324} and 2008 HU_4, but at longer time of flights. In addition, maybe several flybys instead of just one could improve Δv results, obtaining, in the other hand, worse times of

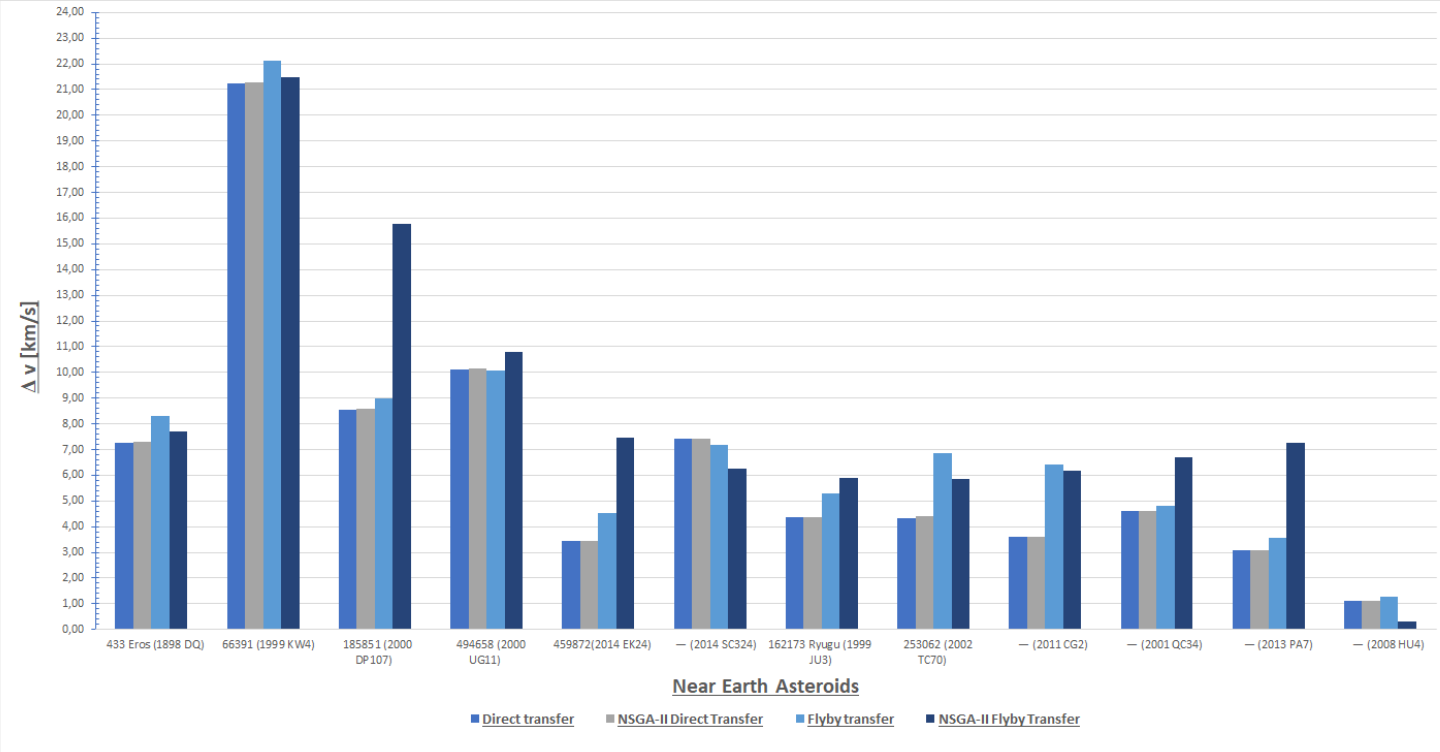

Figure 4.5: Genes population and generations variation

flight. Flybys with other bodies should be also considered, for example with the Moon, like the one propossed by mission Destiny+ by JAXA[1].

Genetic algorithms have shown to be feasible methods for solving direct transfer trajectories with both a population of 50 and 100 genes and 50 and 100 chromosomes, of course lower computational times are achieved in the case of 50 genes and generations. NSGA gives better time than the one day time step straightforward method while being worse than the fifteen and the double iteration methods but its results are both optimized in time of fligh and Δv, showing better TOF for similar costs. However, in the flyby problem NSGA does not seem to be such as good as in the direct transfer, requiring higher times and a larger number of generations, but as said before, lower Δv would be needed for both flyby calculation method.

The results that have been shown in the previous sections have been optimized to give minimum Δv, nevertheless this is no the only factor that should be taken into account. Time of flight should be considered when choosing possible NEAs to exploit. As it was shown in Section 1.1, mineral prices may change from year to year and Net Present Values, Section 1.2.3, that consider long times would deal with bigger uncertainties and lower values of the present value. Therefore, frequency of the mining epochs and the time that long each one should also be considered.

All conclusions that have been exposed here refer only to optimum Δv transfer orbits and to their times. However, profitability of a NEA is not only a factor of its accesibility. As introduced

[1] http://www.isas.jaxa.jp/j/researchers/symp/sss13/paper/P2-132.pdf

in Section 2.3, the minearology and the size of the NEA can change its price value. Asteroids that can be reached with lower Δv less profitable than others that are more expensive if its associated price value is low, for example. Taking a look at table 2.5, it can be seeing that minearology information and spectral is known only for a few NEAs, and the same occurs with the size. More observations and measurements would be needed to determine a higher number of feasible NEAs.

Another constrain of this work comes with the fact that it only applies to impulsive maneuvers and therefore to chemical propulsion. Ionic engines could be used instead, changing the maneuvers and therefore the Δv required to get to NEAs. Missions whose target has been NEAs have used this kind of propulsion and in fact, they have taking advanced of the gravity assits maneuvers. This suggest that flyby could be used to optimize orbits stablished by ionic propulsion. In addition, in the case of Hayabusa II, the gravity assits increased its total velocity in its swing by, which could give better Δv performance. Therefore, both ionic propulsion and others patched conic methods could be consider in similar works, giving some insight in the field.

Appendix A

HORIZONS request standard

```
*******************************************************************************
JPL/HORIZONS                 433 Eros (1898 DQ)           2017-Sep-12 10:23:27
Rec #:   433 (+COV)   Soln.date: 2017-Jun-06_06:20:43   # obs: 6084 (1963-2017)

IAU76/J2000 helio. ecliptic osc. elements (au, days, deg., period=Julian yrs):

  EPOCH=  2451960.5 ! 2001-Feb-20.00 (TDB)         Residual RMS= .38501
   EC= .2229072631692741   QR= 1.133196715533832   TP= 2452085.0842564595
   OM= 304.4109224241166   W=  178.6283757931986   IN= 10.82944804139757
   A= 1.458251585461255    MA= 290.2701786435418   ADIST= 1.783306455388678
   PER= 1.76099            N= .559700089           ANGMOM= .020250272
   DAN= 1.78316            DDN= 1.13326            L= 123.0637166
   B= .2576845             MOID= .14882299         TP= 2001-Jun-24.5842564595

Asteroid physical parameters (km, seconds, rotational period in hours):
   GM= .0004463            RAD= 8.42               ROTPER= 5.27
   H= 11.16                G= .460                 B-V= .921
                           ALBEDO= .250            STYP= S

ASTEROID comments:
1: soln ref.= JPL#611, OCC=0           radar( 1 delay, 3 Dop.)
2: source=ORB
********************************************************************************
```

```
*******************************************************************************
Ephemeris / WWW_USER Tue Sep 12 10:23:27 2017 Pasadena, USA      / Horizons
*******************************************************************************
Target body name: 433 Eros (1898 DQ)              {source: JPL#611}
Center body name: Sun (10)                        {source: DE431}
Center-site name: BODY CENTER
*******************************************************************************
Start time      : A.D. 2020-Jan-01 00:00:00.0000 TDB
Stop  time      : A.D. 2029-Dec-31 00:00:00.0000 TDB
Step-size       : 1440 minutes
*******************************************************************************
Center geodetic : 0.00000000,0.00000000,0.0000000 {E-lon(deg),Lat(deg),Alt(km)}
Center cylindric: 0.00000000,0.00000000,0.0000000 {E-lon(deg),Dxy(km),Dz(km)}
Center radii    : 696000.0 x 696000.0 x 696000.0 k{Equator, meridian, pole}
Small perturbers: Yes                             {source: SB431-N16}
Output units    : KM-S
Output type     : GEOMETRIC cartesian states
Output format   : 2 (position and velocity)
Reference frame : ICRF/J2000.0
Coordinate systm: Ecliptic and Mean Equinox of Reference Epoch
*******************************************************************************
Initial IAU76/J2000 heliocentric ecliptic osculating elements (au, days, deg.):
  EPOCH=  2451960.5 ! 2001-Feb-20.00 (TDB)          Residual RMS= .38501
   EC= .2229072631692741   QR= 1.133196715533832   TP= 2452085.0842564595
   OM= 304.4109224241166   W=  178.6283757931986   IN= 10.82944804139757
  Equivalent ICRF heliocentric equatorial cartesian coordinates (au, au/d):
   X= 1.232462280518342E+00  Y= 4.853585833335238E-01  Z= 4.982485077937658E-01
  VX=-9.498420974073860E-03 VY= 1.037188518492748E-02 VZ= 4.180083004990690E-03
Asteroid physical parameters (km, seconds, rotational period in hours):
   GM= .0004463            RAD= 8.42               ROTPER= 5.27
   H= 11.16                G= .460                 B-V= .921
                           ALBEDO= .250            STYP= S
```

```
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            JDTDB,            Calendar Date (TDB),                      X,
                               Y,                       Z,                      VX,
                                                     VY,                      VZ,
*******************************************************************************
*******************************************************************************
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17639824256859E+08,  2.748215348887712E+06,  1.507944235344202E+01,  1.21014960
1668715E+01,  3.687729358116847E+00
...
...
...
$$EOE
*******************************************************************************
*******************************************************************************
************************************
Coordinate system description:

  Ecliptic and Mean Equinox of Reference Epoch

    Reference epoch: J2000.0
    XY-plane: plane of the Earth's orbit at the reference epoch
              Note: obliquity of 84381.448 arcseconds wrt ICRF equator (IAU76)
    X-axis  : out along ascending node of instantaneous plane of the Earth's
              orbit and the Earth's mean equator at the reference epoch
    Z-axis  : perpendicular to the xy-plane in the directional (+ or -) sense
              of Earth's north pole at the reference epoch.

  Symbol meaning:

    JDTDB    Julian Day Number, Barycentric Dynamical Time
      X      X-component of position vector (km)
      Y      Y-component of position vector (km)
      Z      Z-component of position vector (km)
      VX     X-component of velocity vector (km/sec)
      VY     Y-component of velocity vector (km/sec)
      VZ     Z-component of velocity vector (km/sec)

Geometric states/elements have no aberrations applied.
Computations by ...
     Solar System Dynamics Group, Horizons On-Line Ephemeris System
     4800 Oak Grove Drive, Jet Propulsion Laboratory
```

```
    Pasadena, CA  91109   USA
    Information: http://ssd.jpl.nasa.gov/
    Connect    : telnet://ssd.jpl.nasa.gov:6775  (via browser)
                 http://ssd.jpl.nasa.gov/?horizons
                 telnet ssd.jpl.nasa.gov 6775    (via command-line)
    Author     : Jon.D.Giorgini@jpl.nasa.gov
*******************************************************************************
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Appendix B

Near Earth Asteroid's Orbits

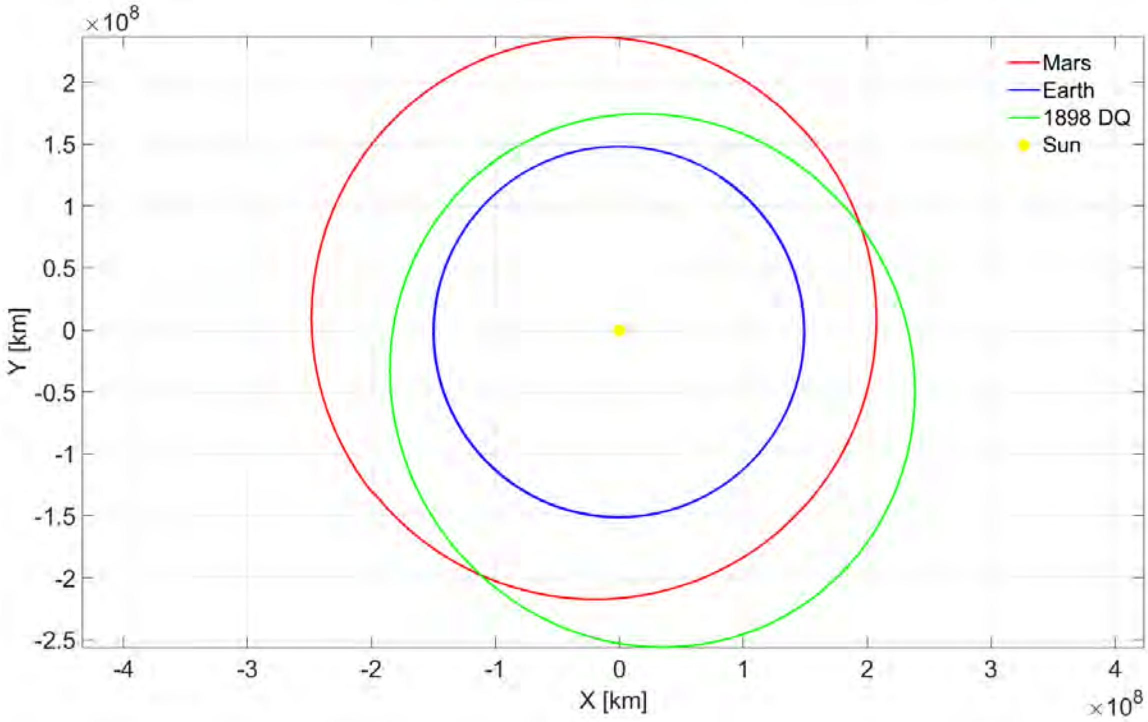

Figure B.1: 433 Eros (1898 DQ)

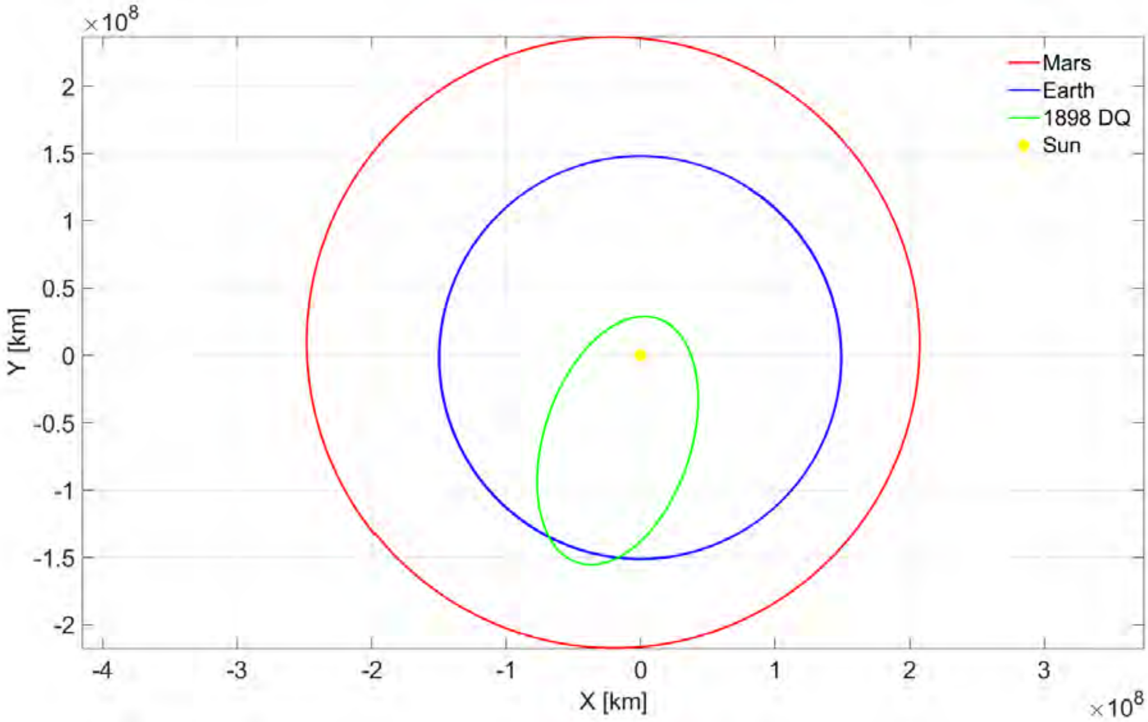

Figure B.2: 66391 (1999 KW_4)

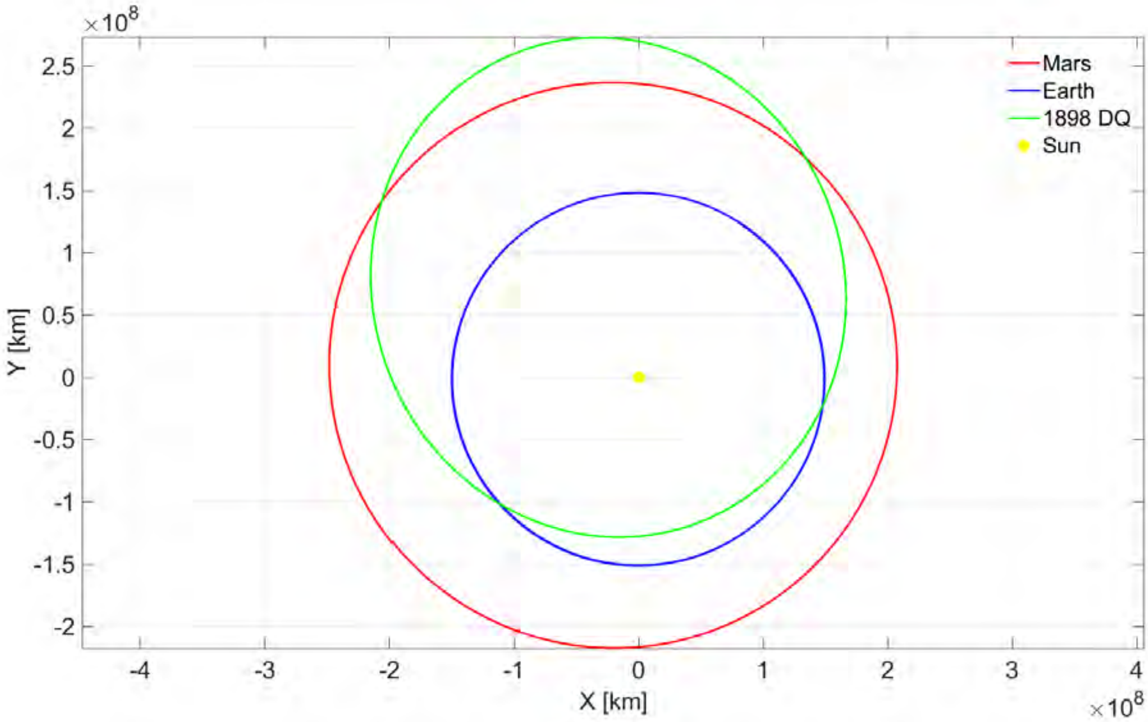

Figure B.3: 185851 (2000 DP_{107})

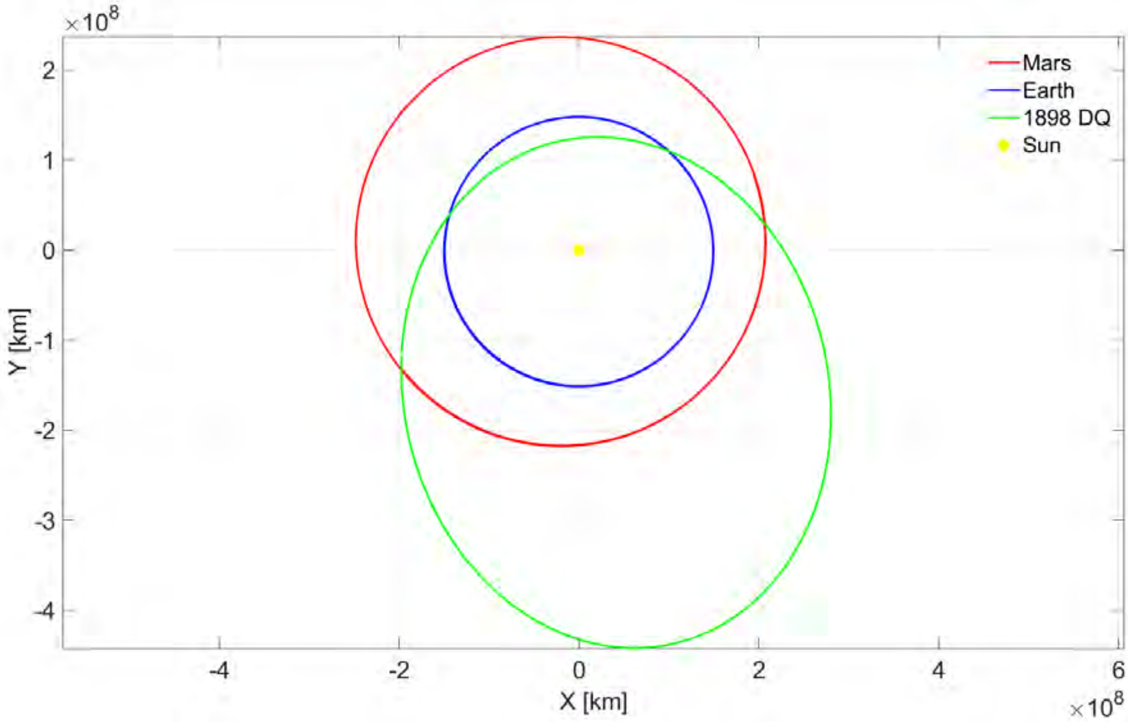

Figure B.4: 494658 (2000 UG_{11})

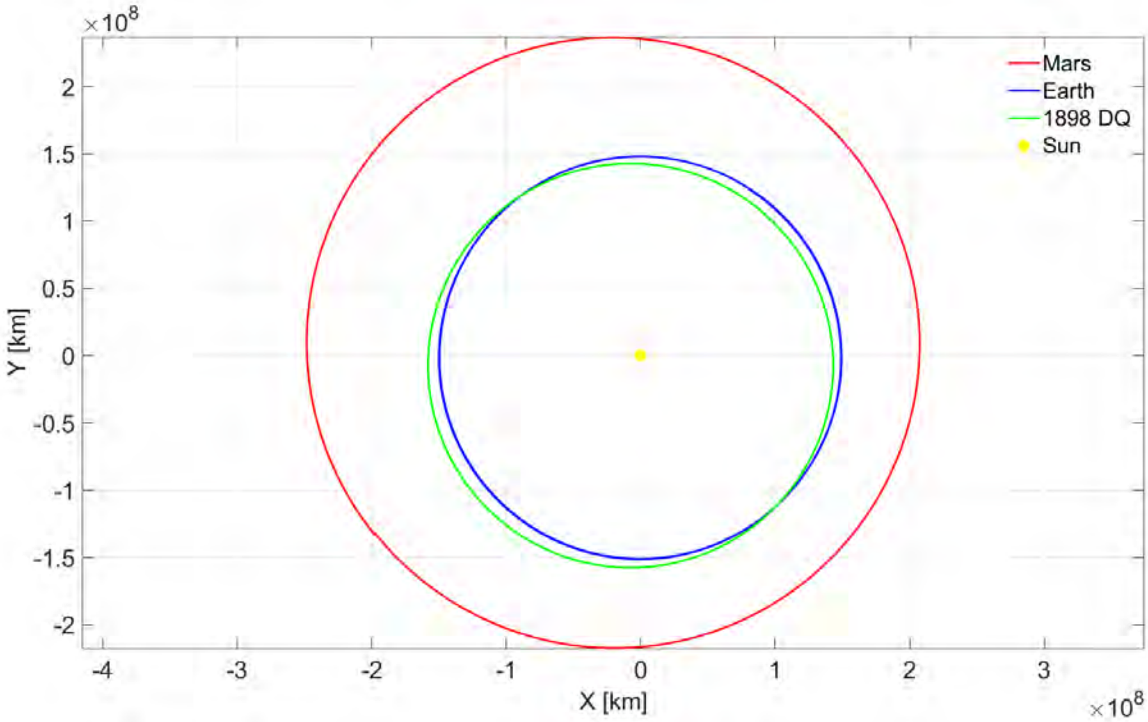

Figure B.5: 459872(2014 EK_{24})

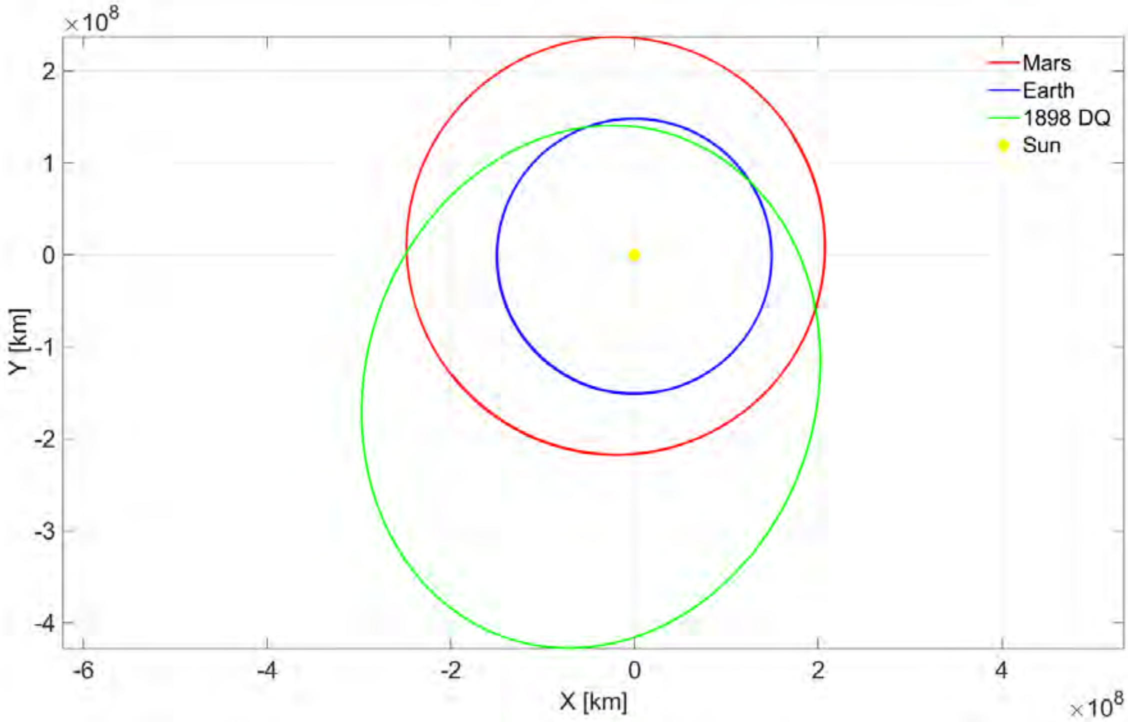

Figure B.6: — (2014 SC_{324})

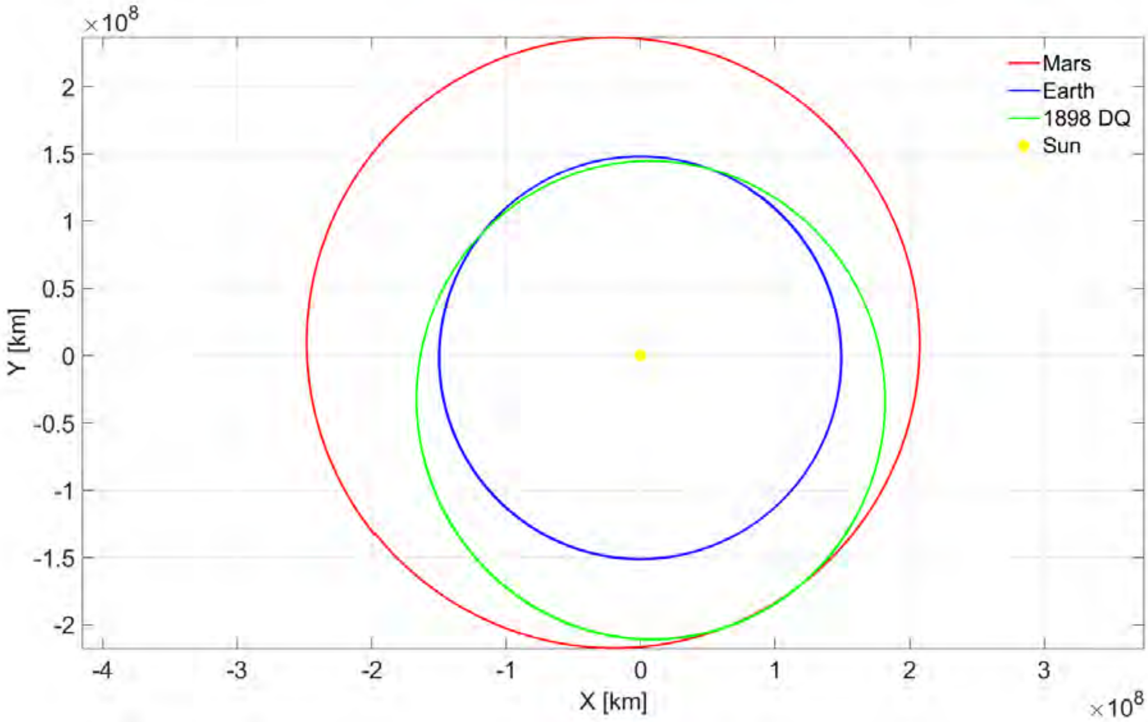

Figure B.7: 162173 Ryugu (1999 JU_3)

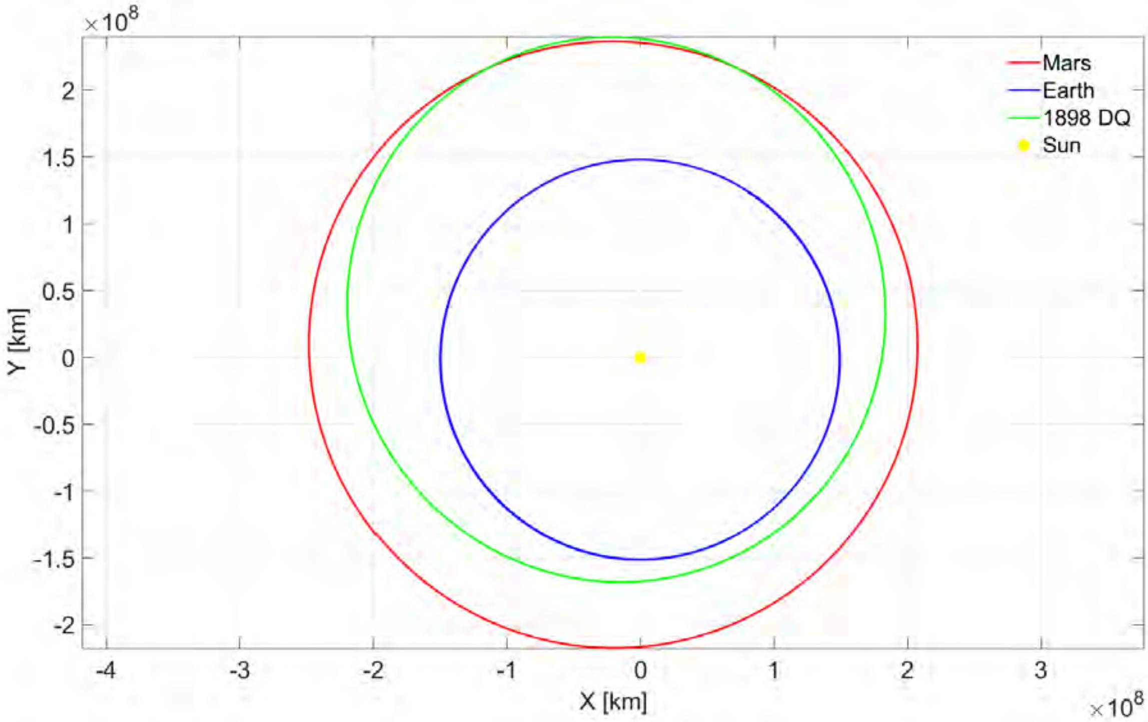

Figure B.8: 253062 (2002 TC_{70})

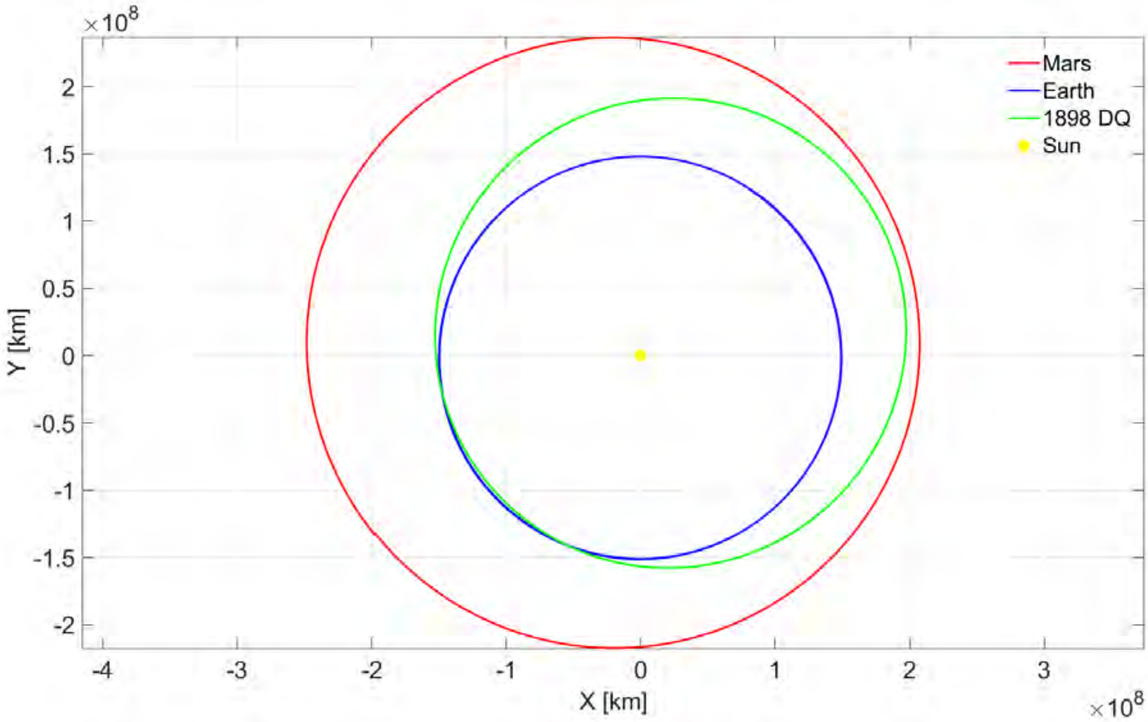

Figure B.9: — (2011 CG_2)

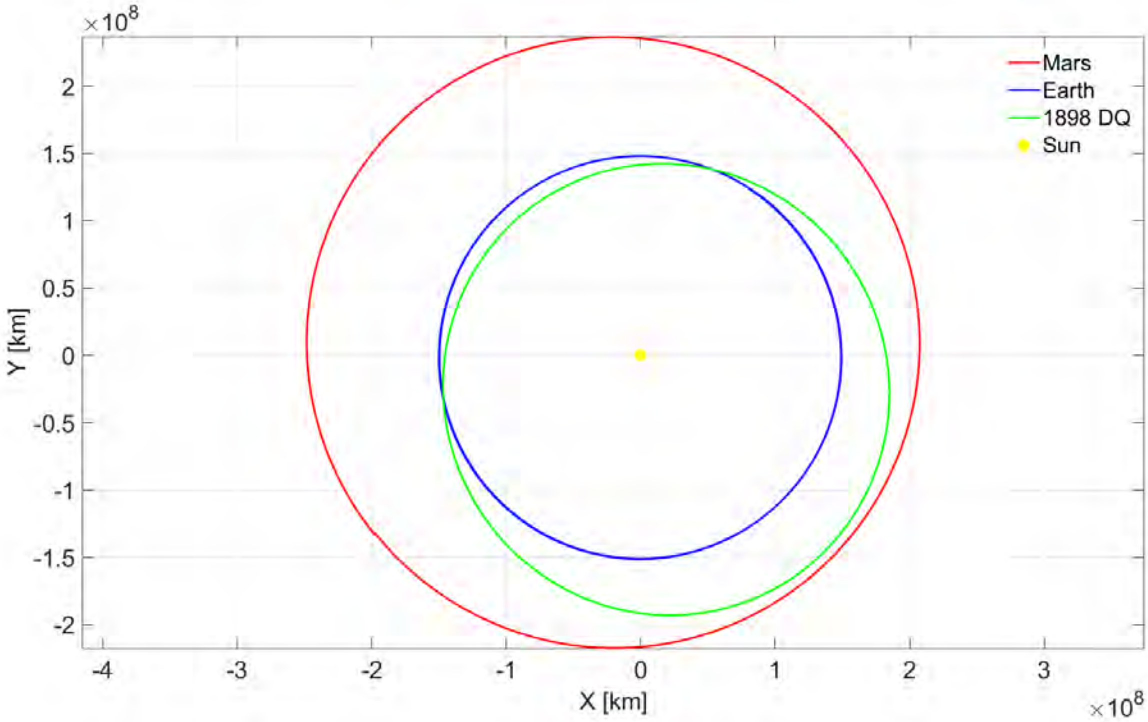

Figure B.10: — (2001 QC_{34})

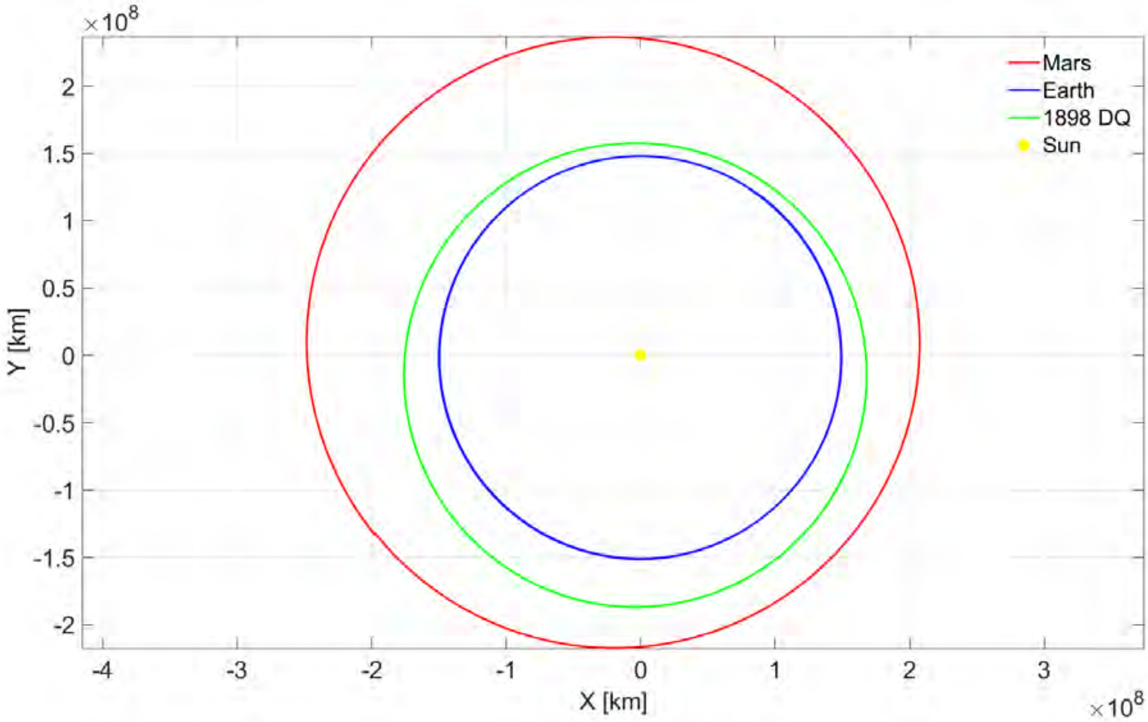

Figure B.11: — (2013 PA_7)

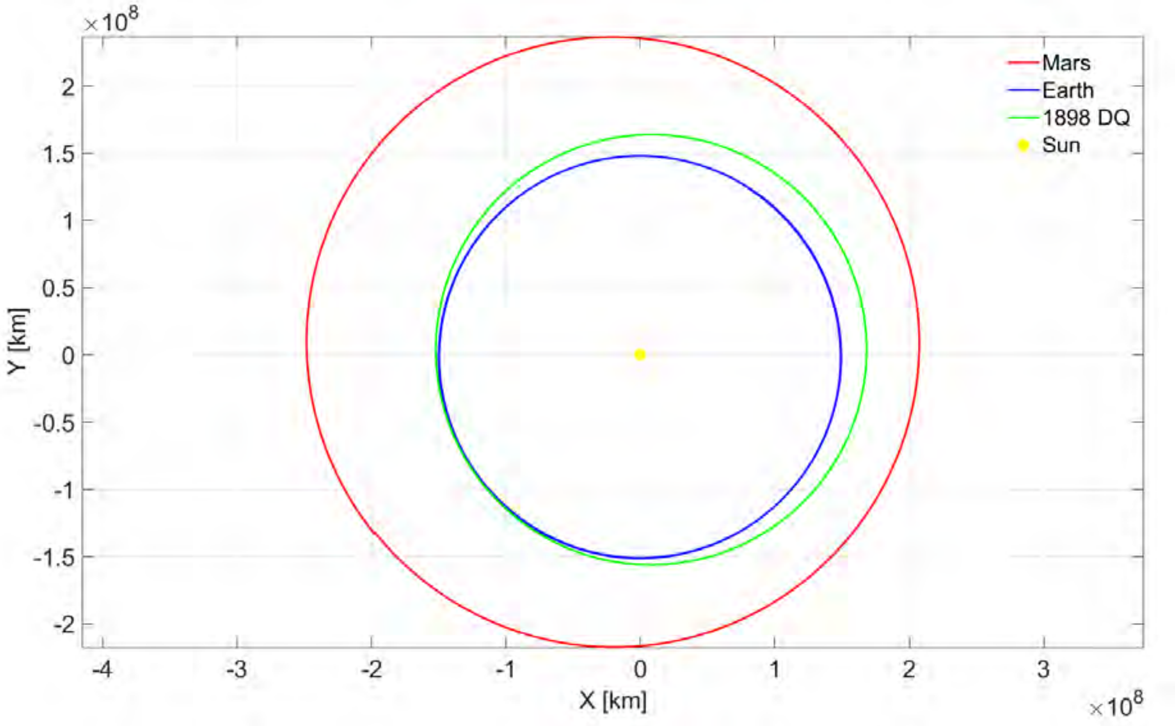

Figure B.12: — (2008 HU_4)

Appendix C

Porkchorp Plots and Trajectories

C.1 Porkchopr Plots

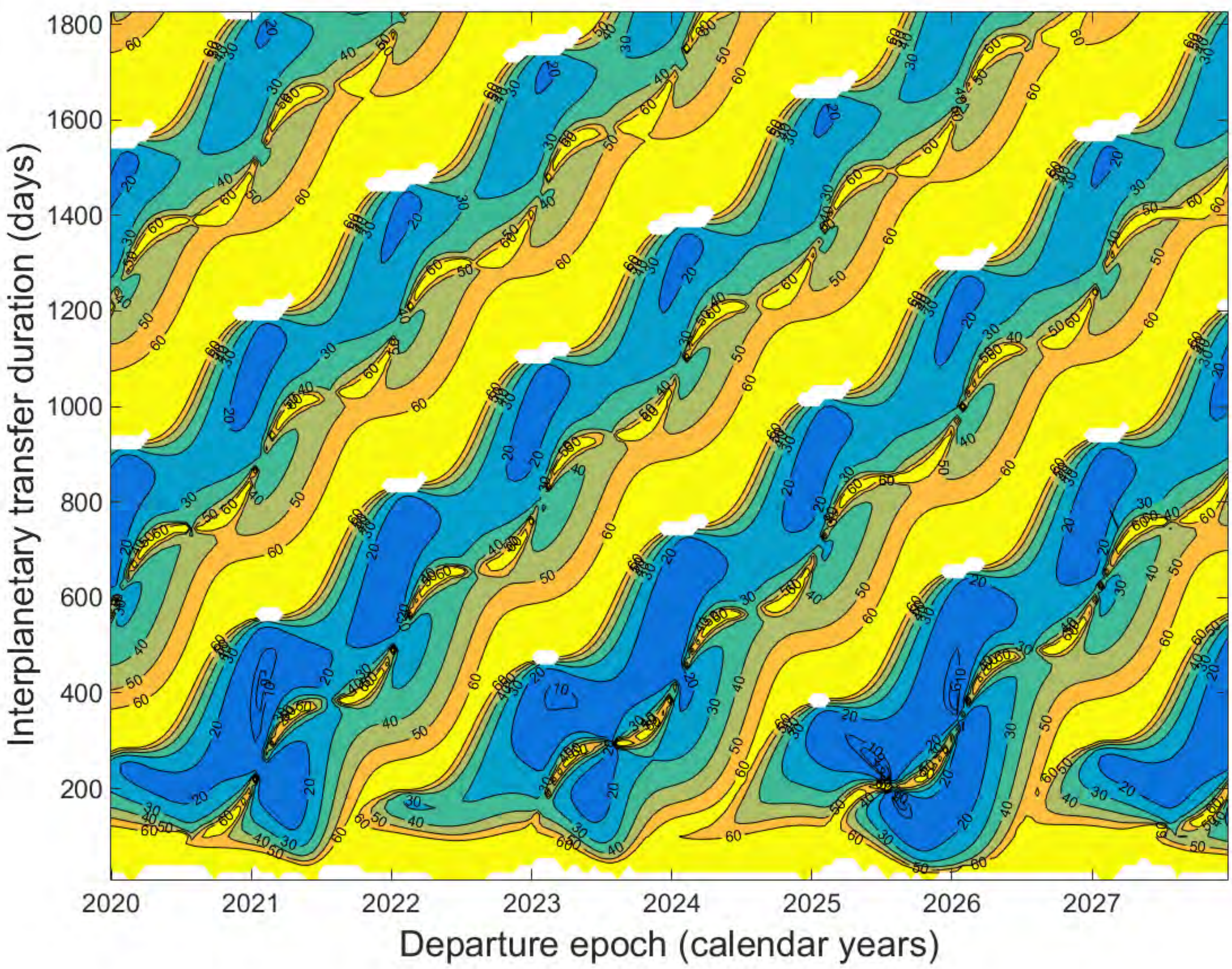

Figure C.1: Porkchop Plot 433 Eros (1898 DQ)

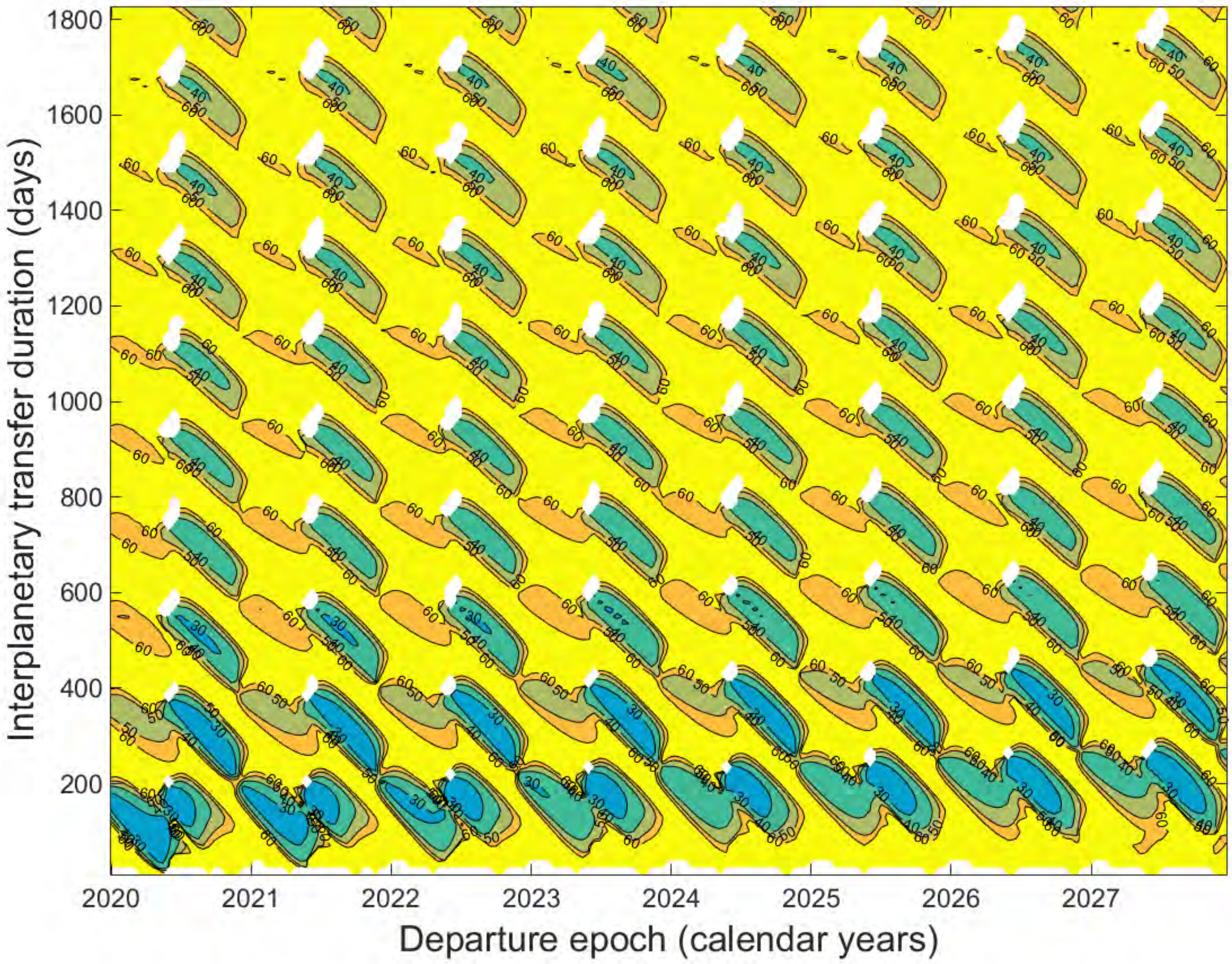

Figure C.2: Porkchop Plot 66391 (1999 KW_4)

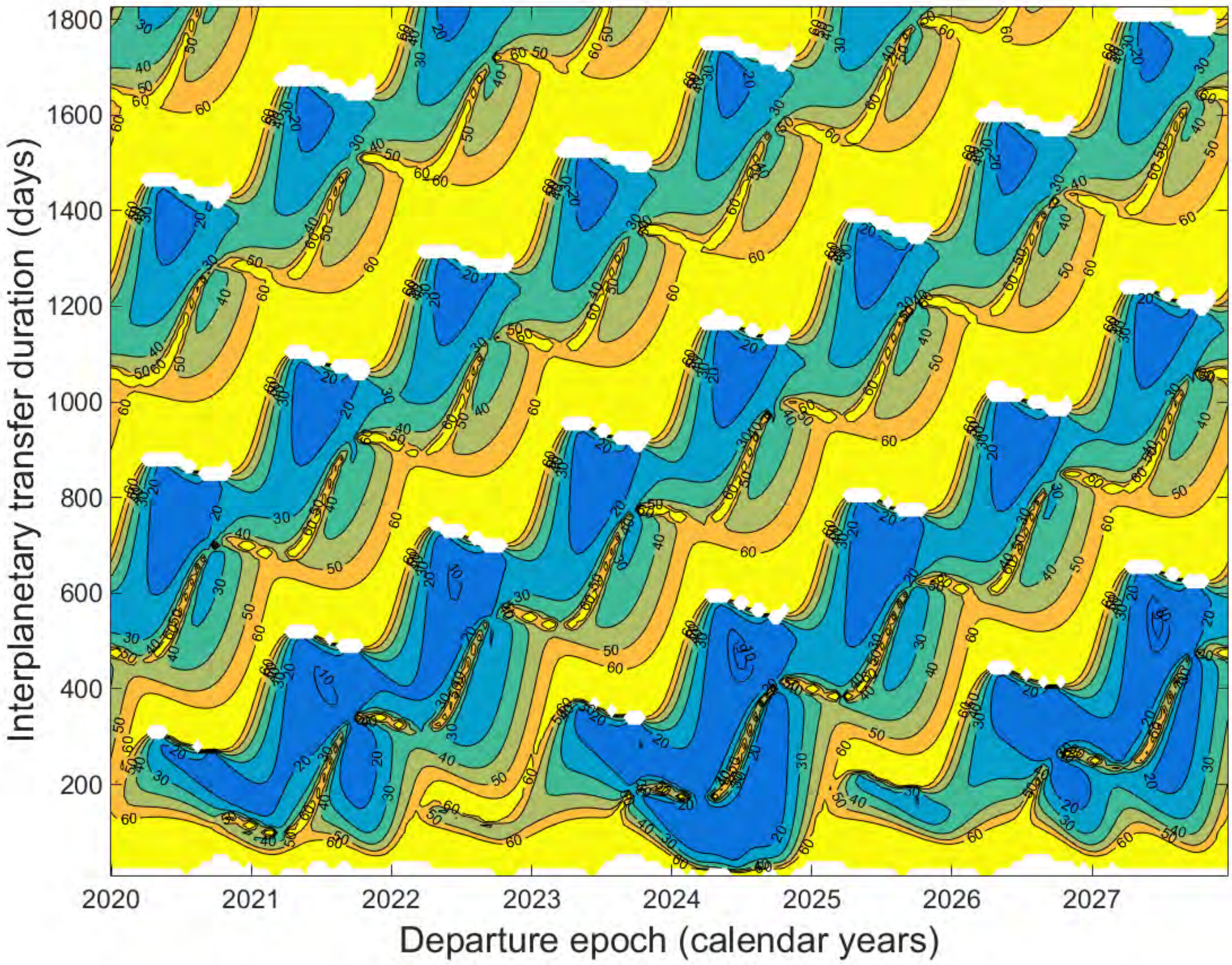

Figure C.3: Porkchop Plot 185851 (2000 DP_{107})

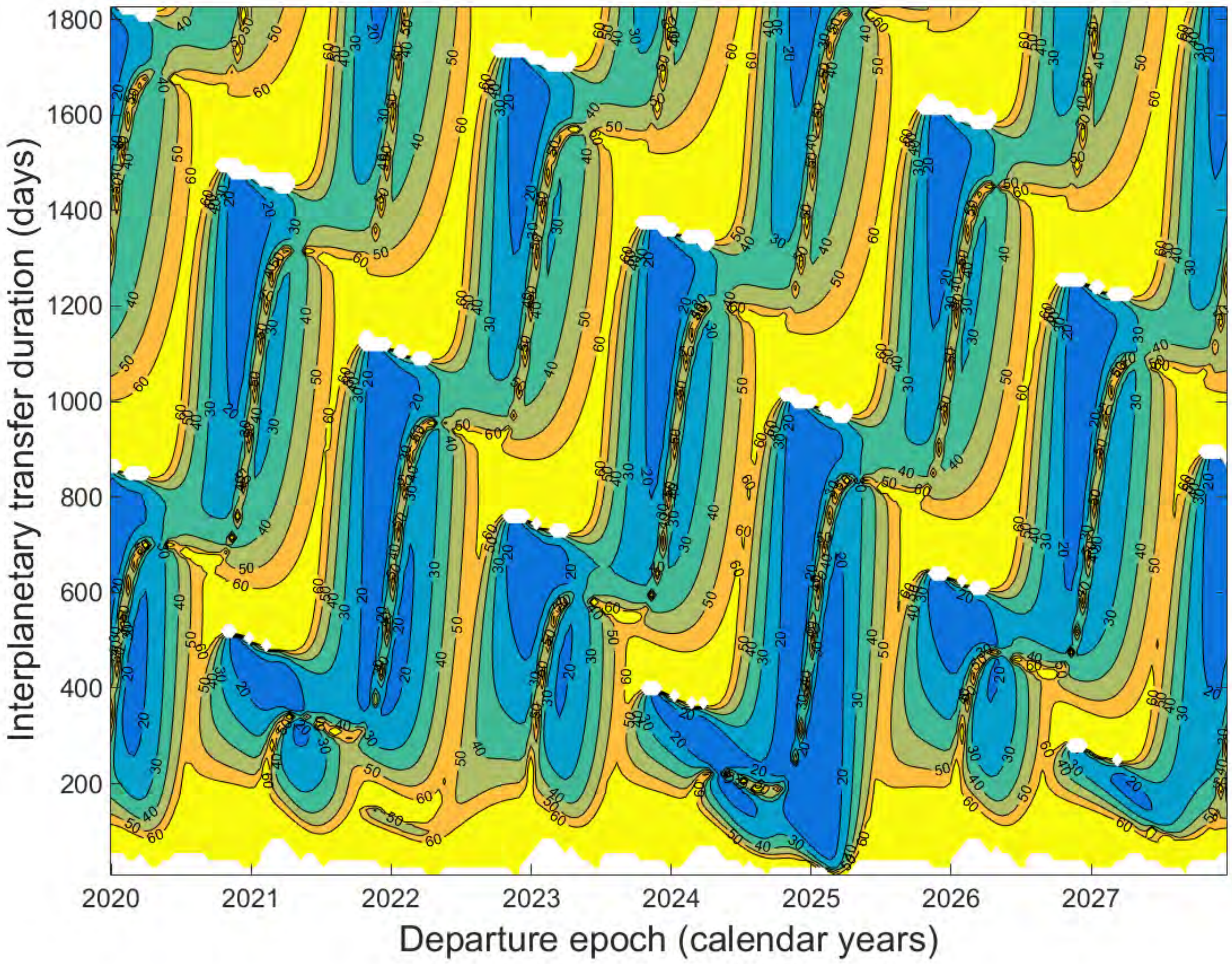

Figure C.4: Porkchop Plot 494658 (2000 UG_{11})

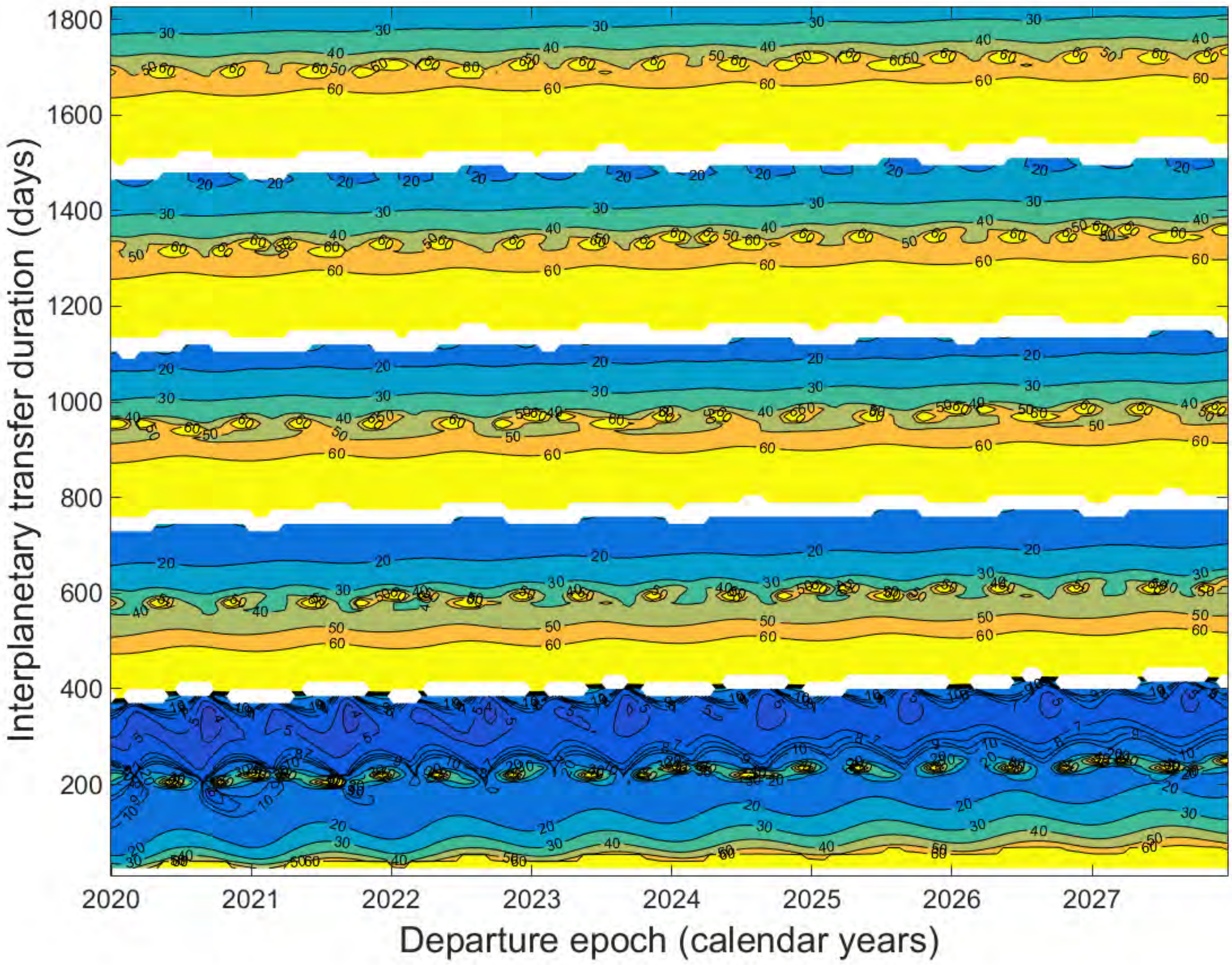

Figure C.5: Porkchop Plot 459872(2014 EK_{24})

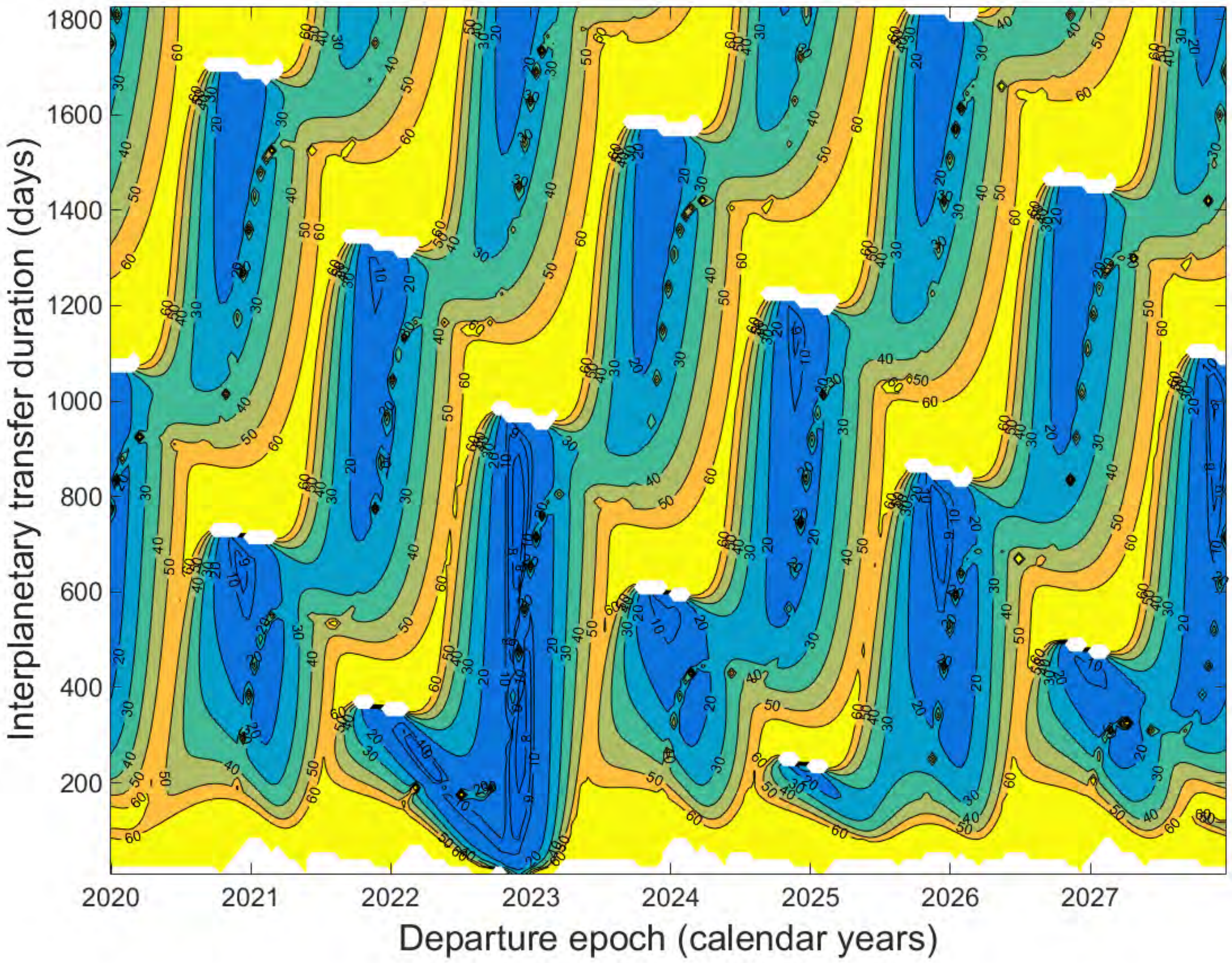

Figure C.6: Porkchop Plot — (2014 SC_{324})

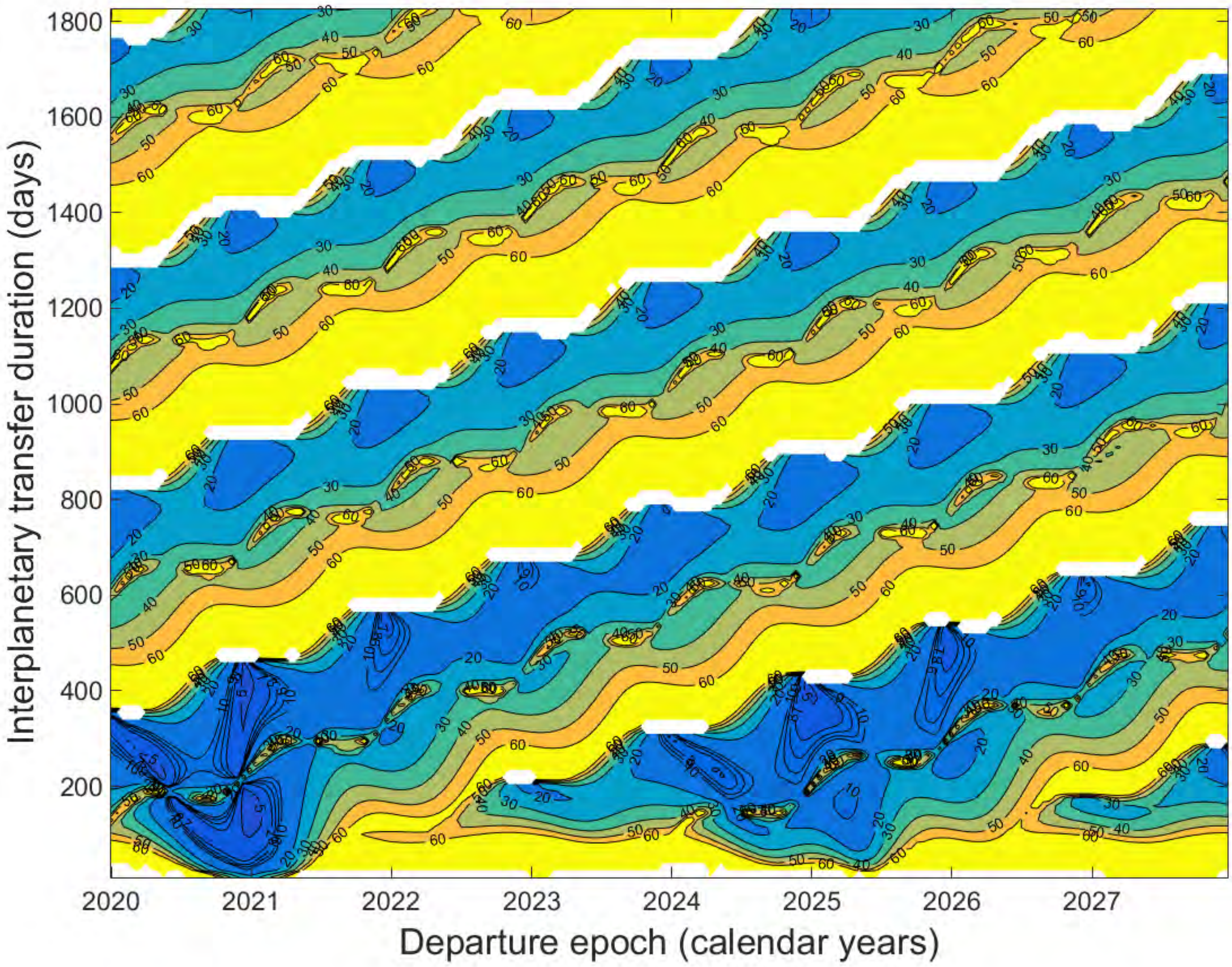

Figure C.7: Porkchop Plot 162173 Ryugu (1999 JU_3)

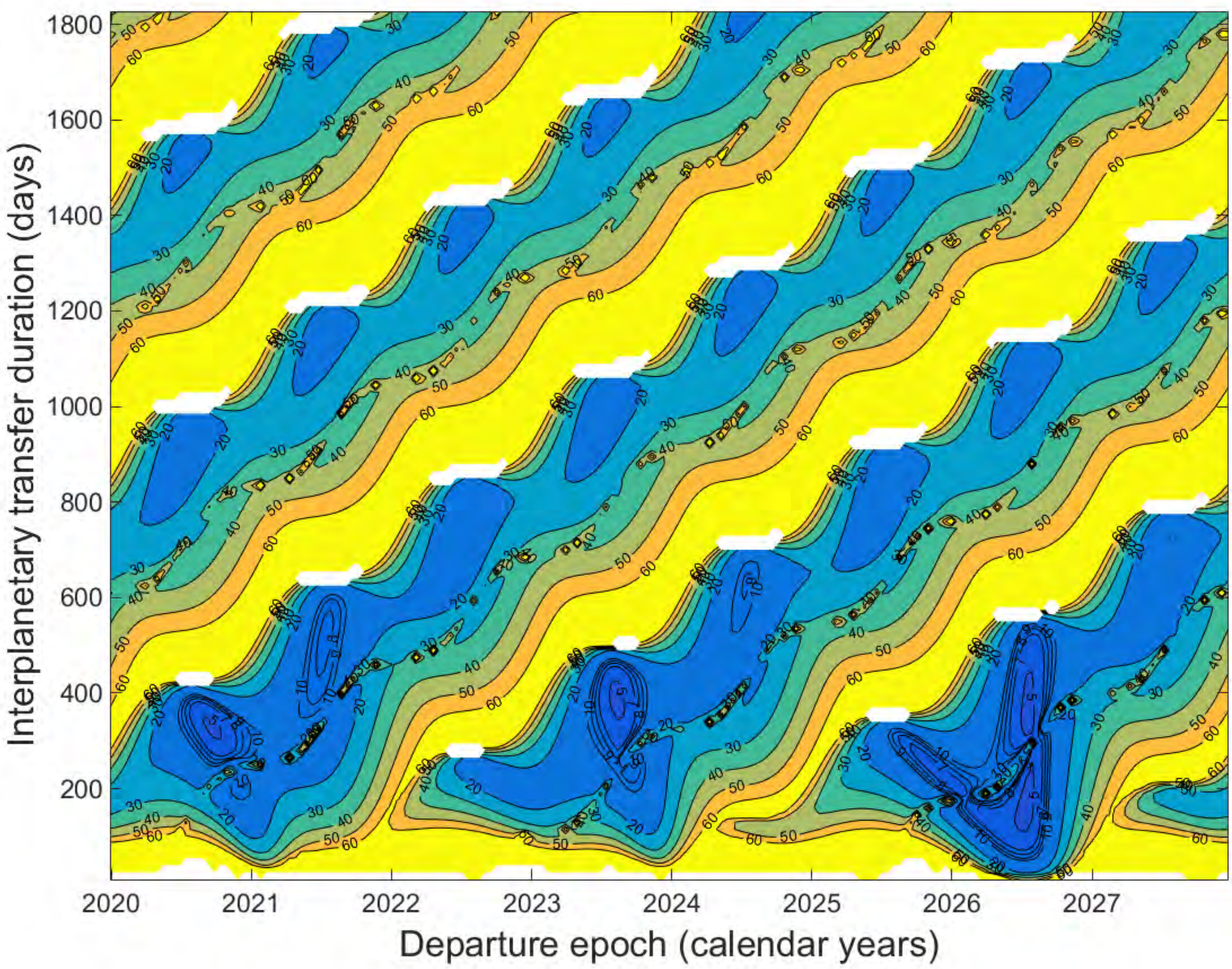

Figure C.8: Porkchop Plot 253062 (2002 TC_{70})

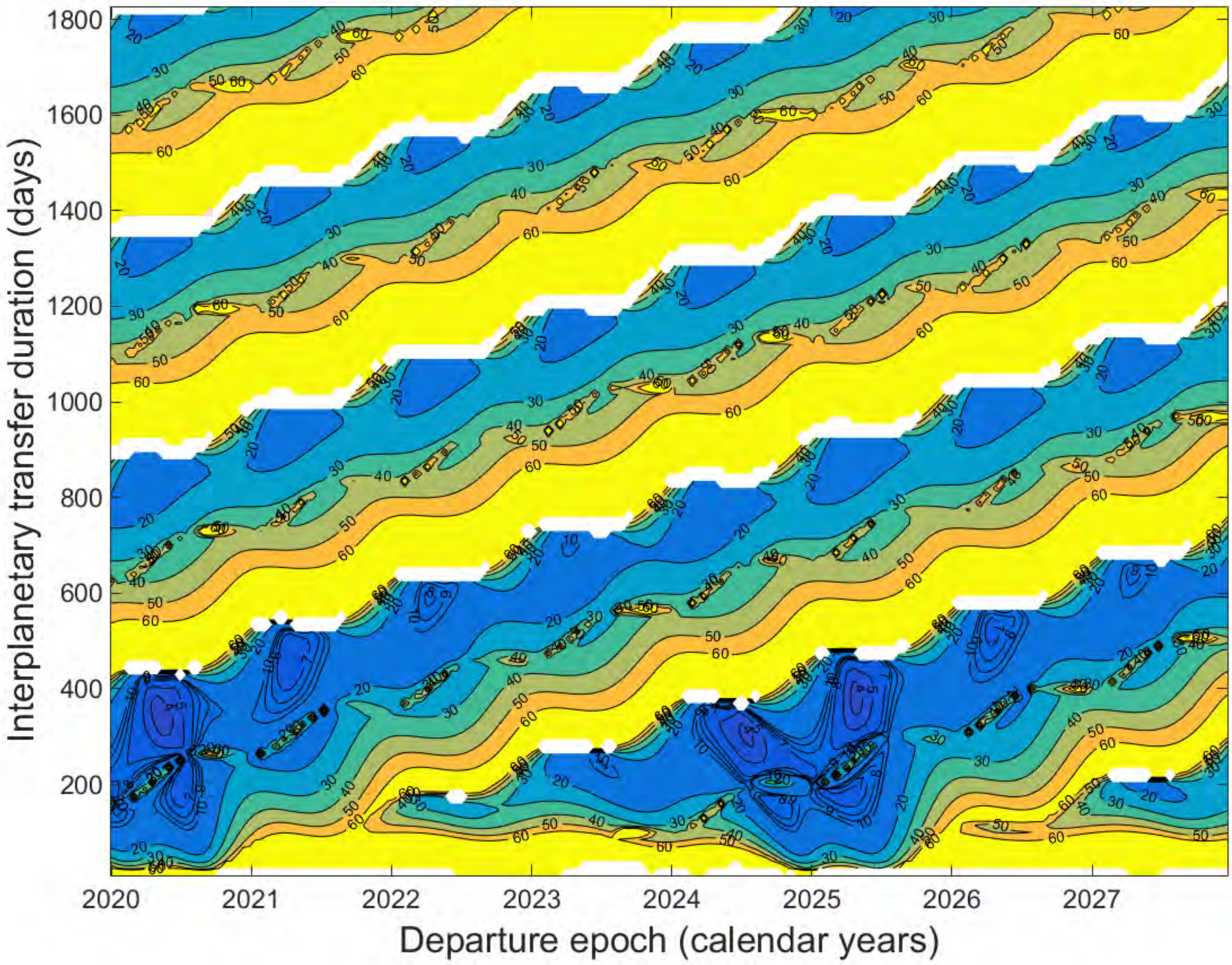

Figure C.9: Porkchop Plot — (2011 CG_2

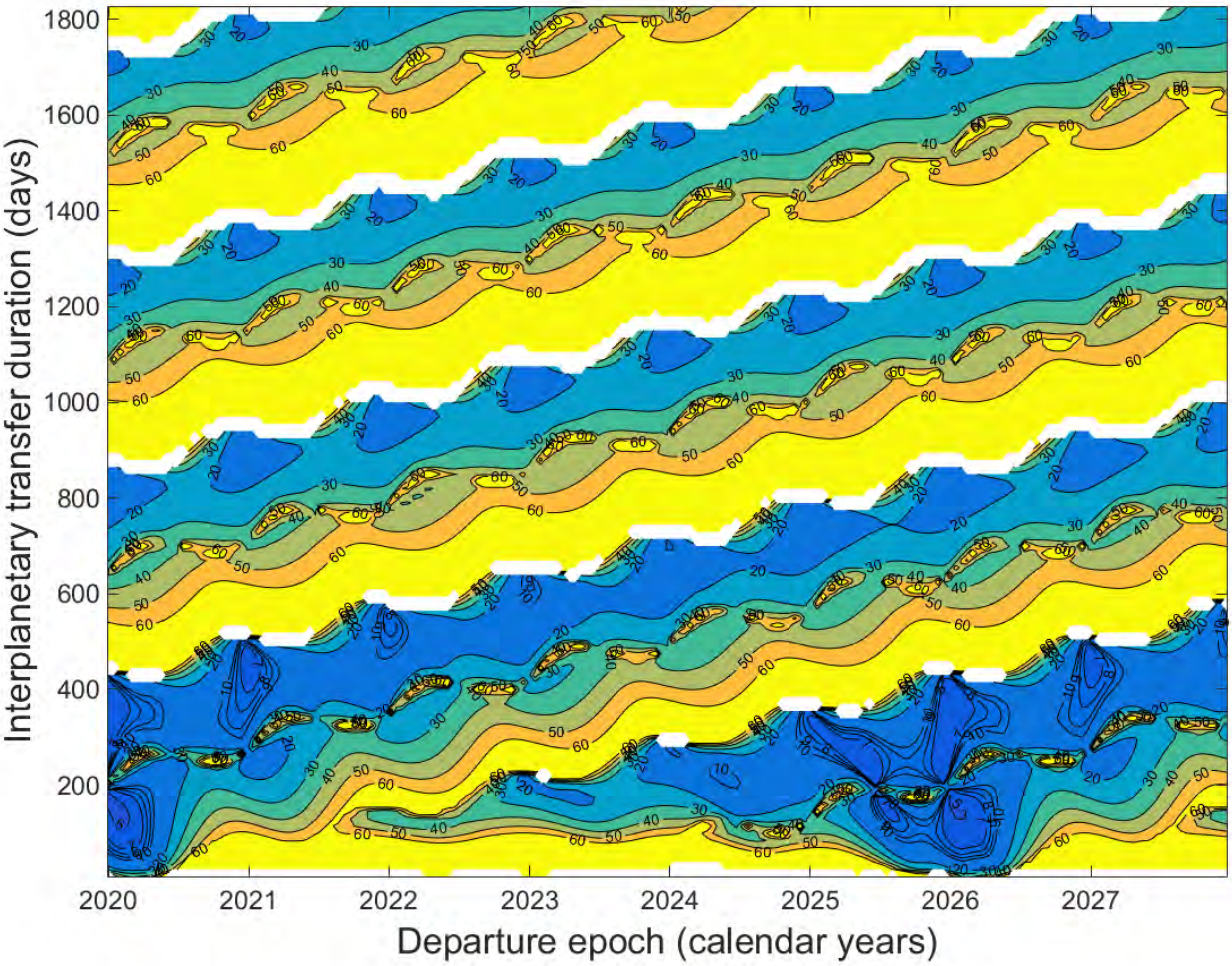

Figure C.10: Porkchop Plot — (2001 QC_{34})

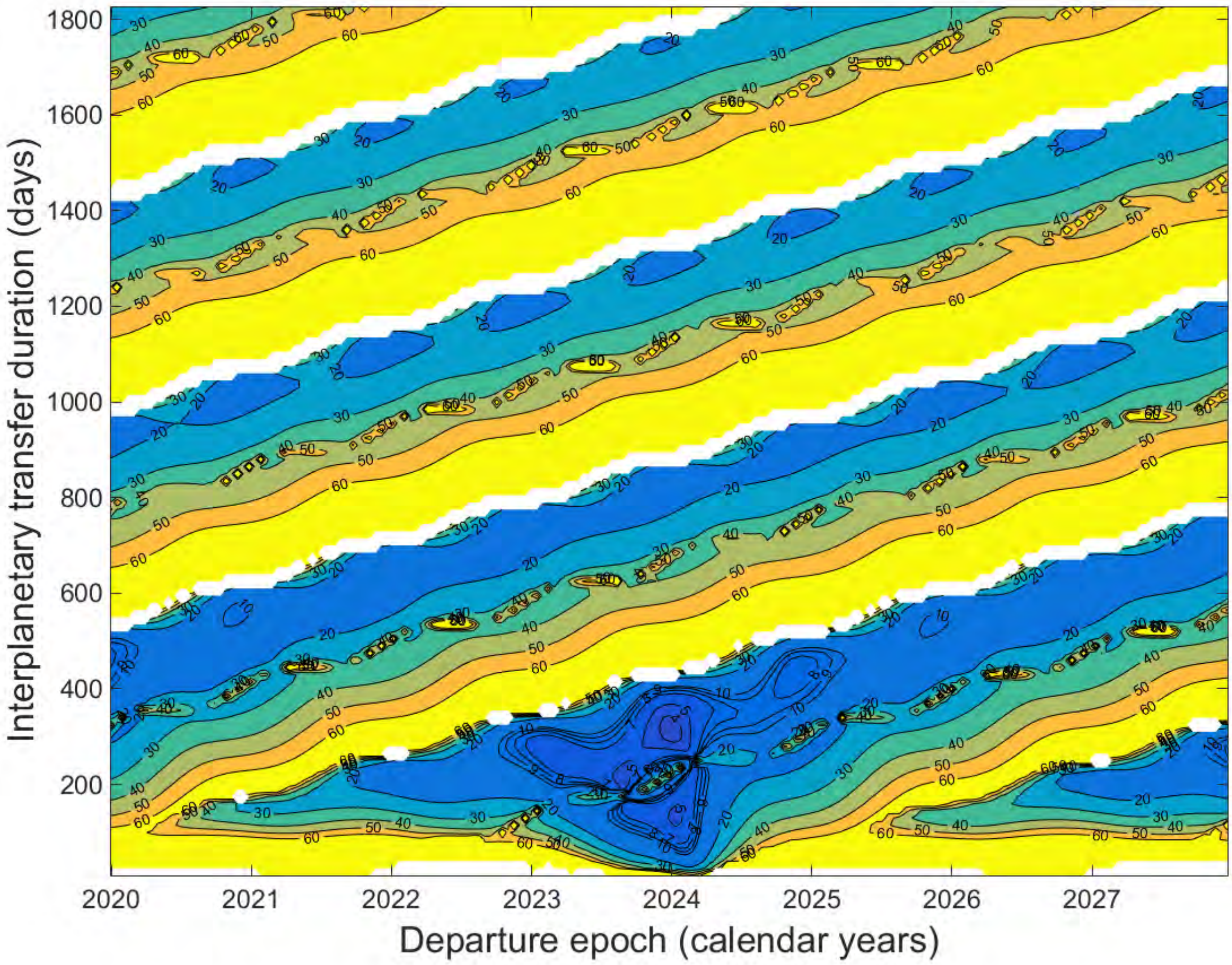

Figure C.11: Porkchop Plot — (2013 PA_7)

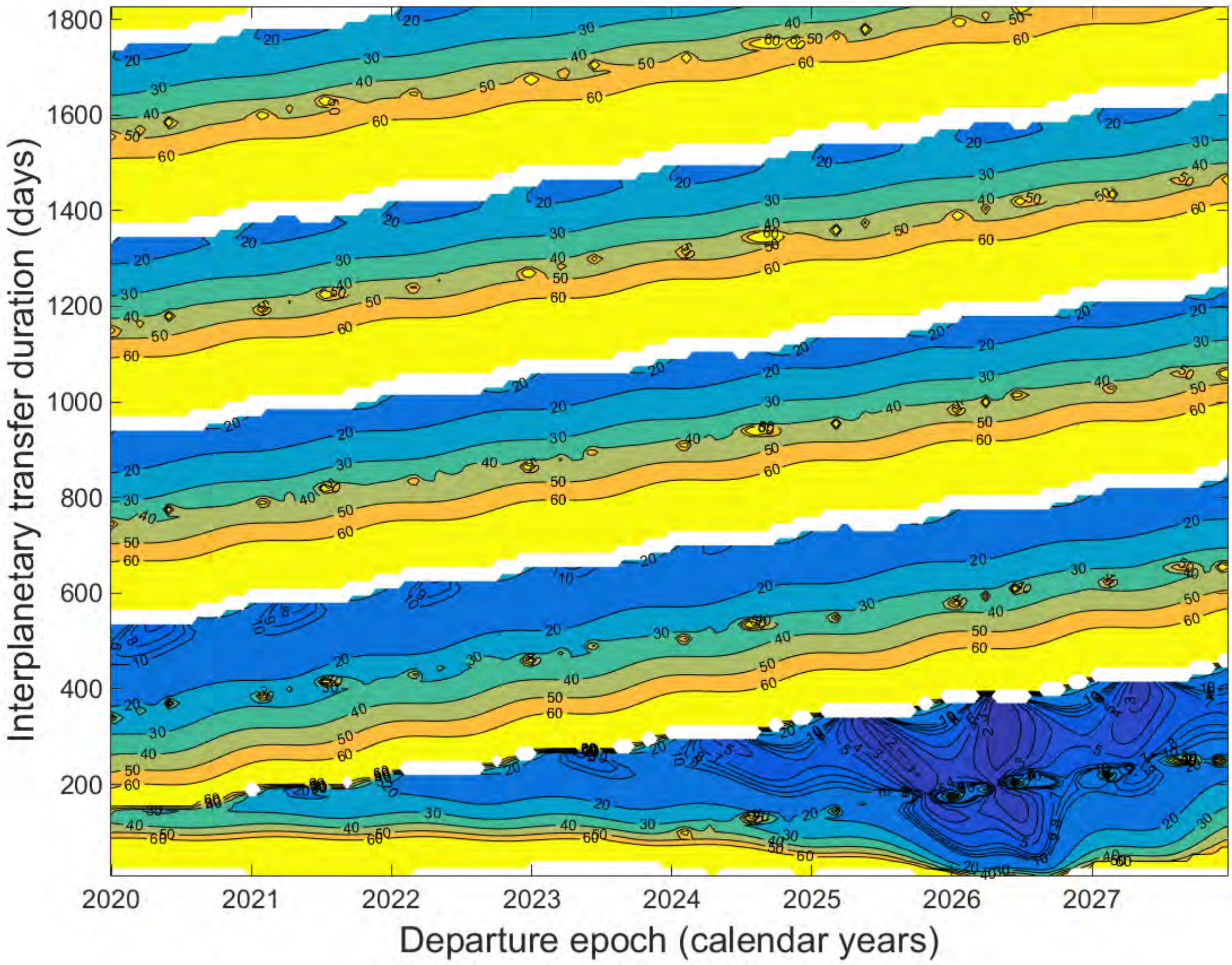

Figure C.12: Porkchop Plot — (2008 HU_4)

C.2 Lambert's Problem Plots

Earth orbits are given as blue curves, while NEAs are the red ones and transfer orbits are the black ones.

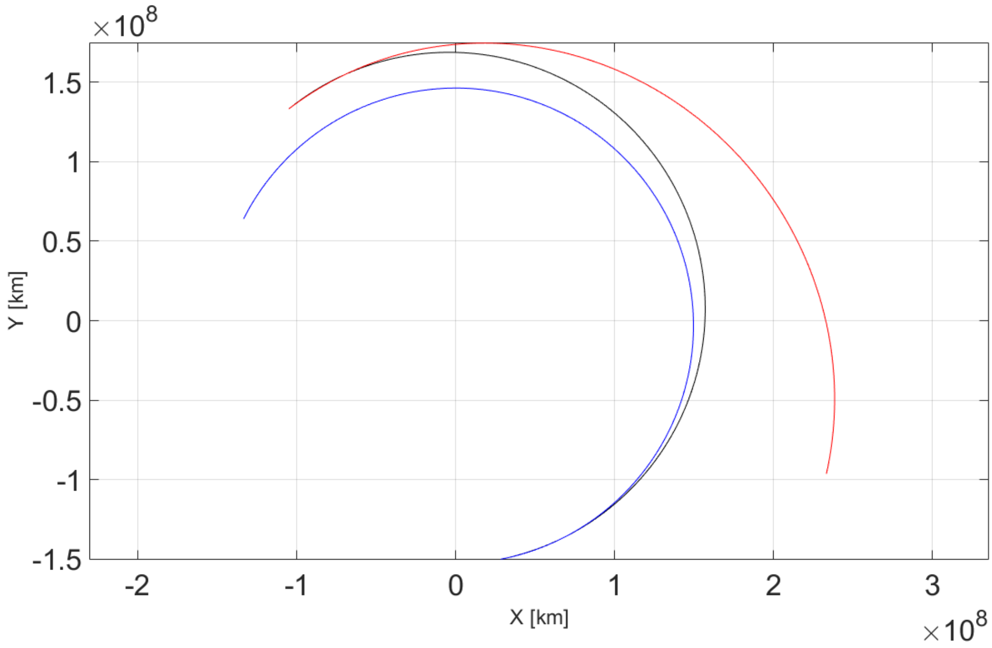

Figure C.13: 433 Eros (1898 DQ)

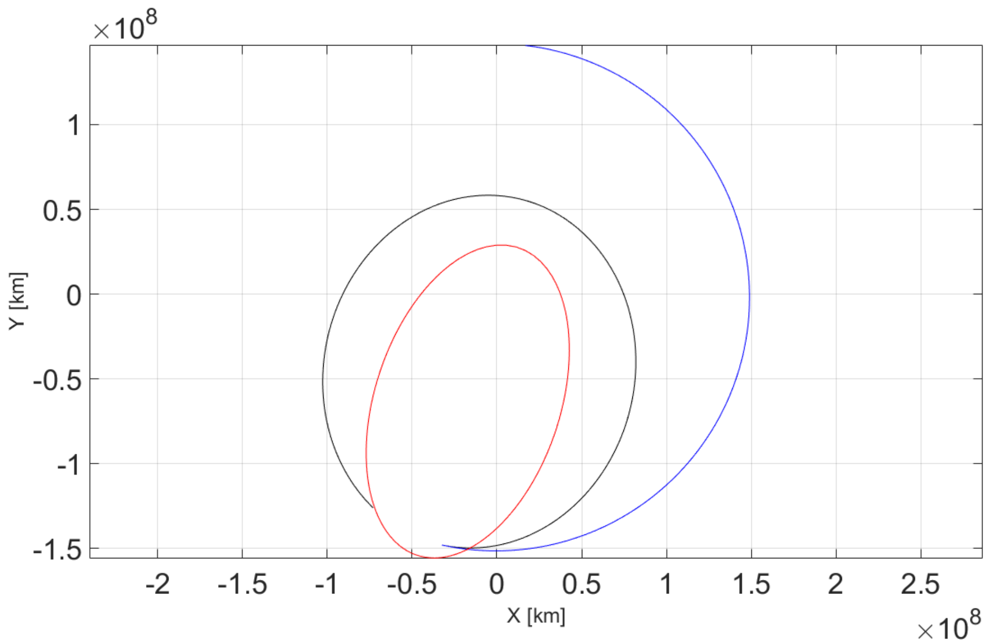

Figure C.14: 66391 (1999 KW_4)

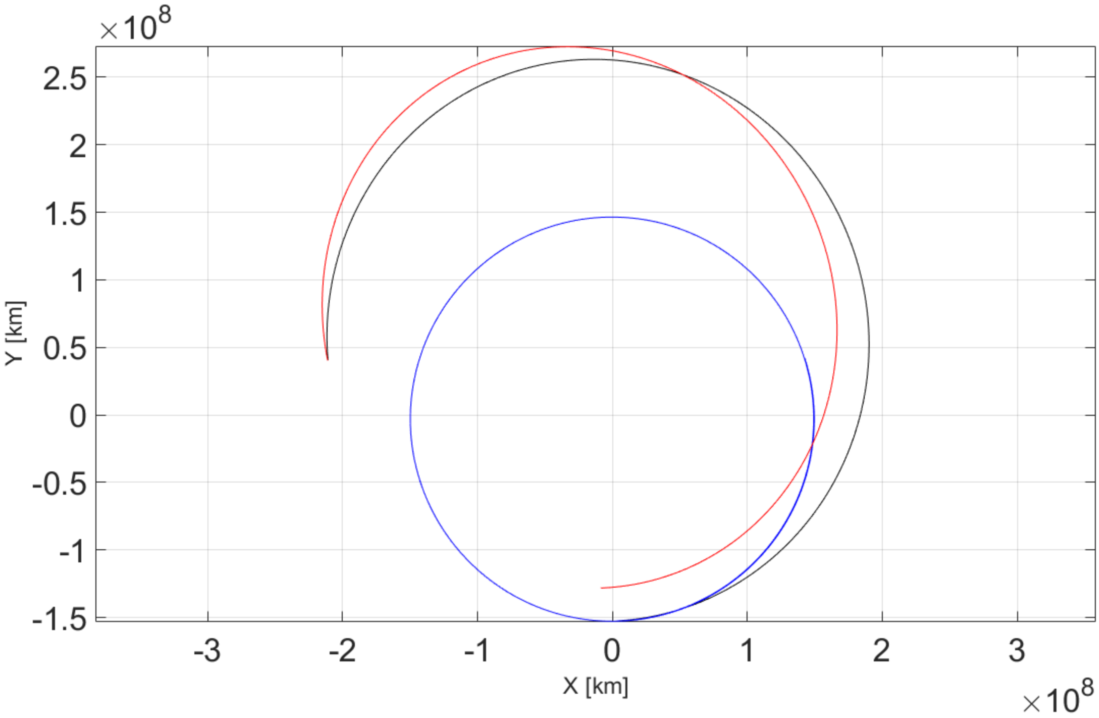

Figure C.15: 185851 (2000 DP_{107})

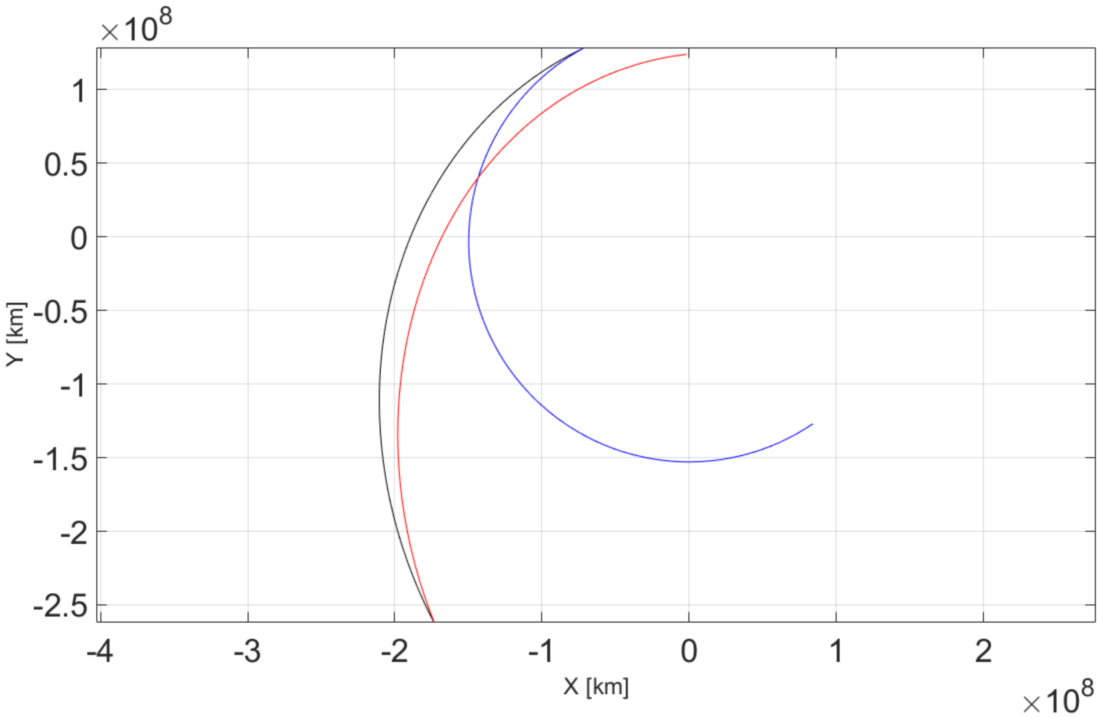

Figure C.16: 494658 (2000 UG_{11})

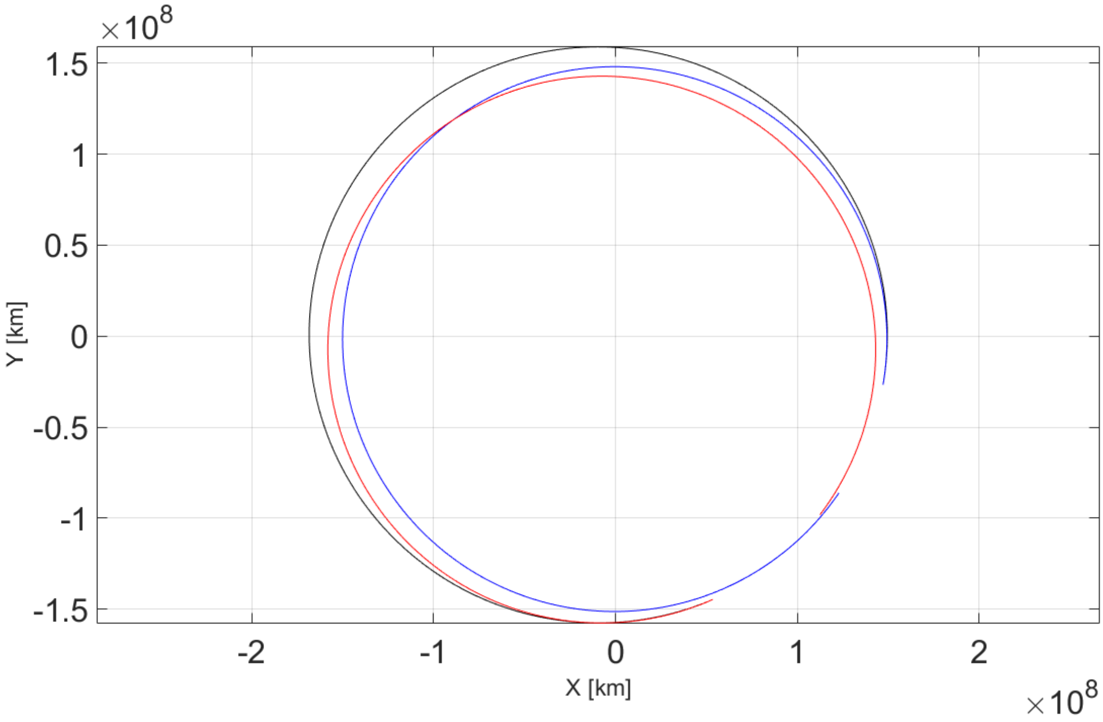

Figure C.17: 459872(2014 EK_{24})

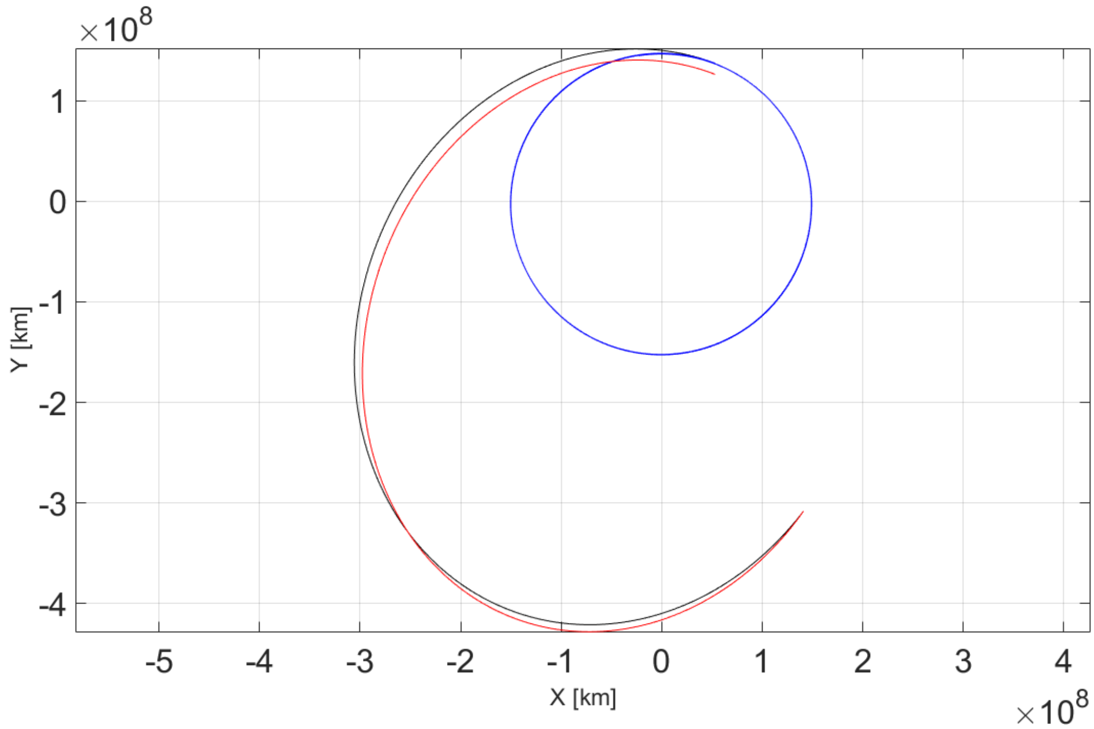

Figure C.18: — (2014 SC_{324})

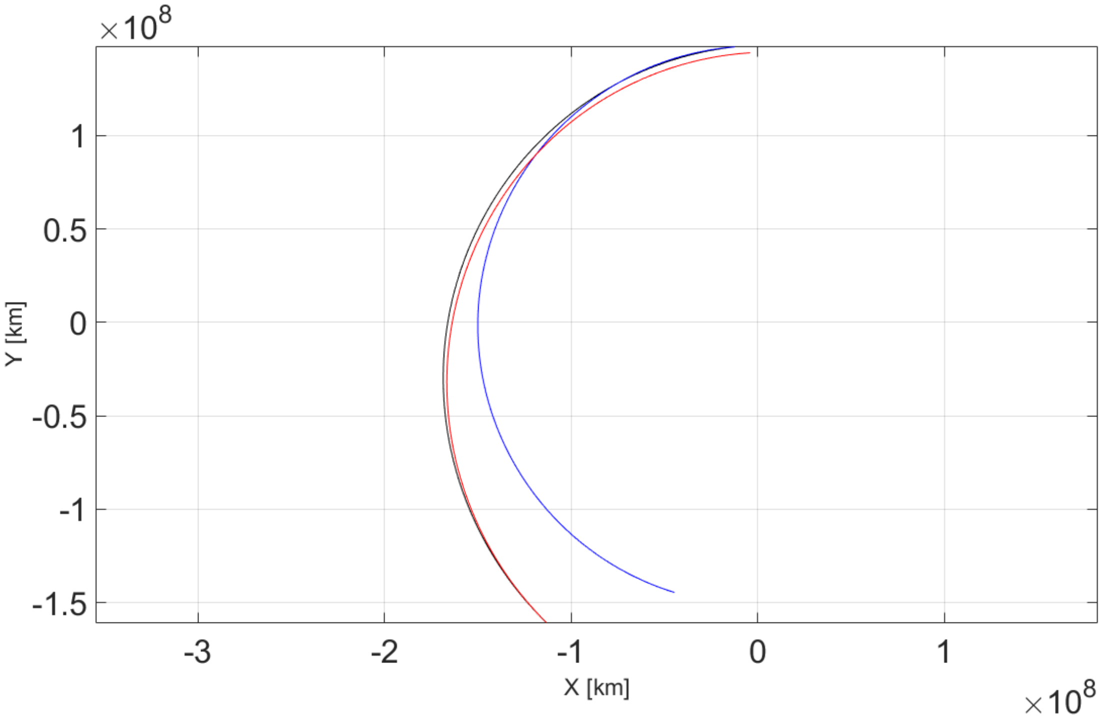

Figure C.19: 162173 Ryugu (1999 JU_3)

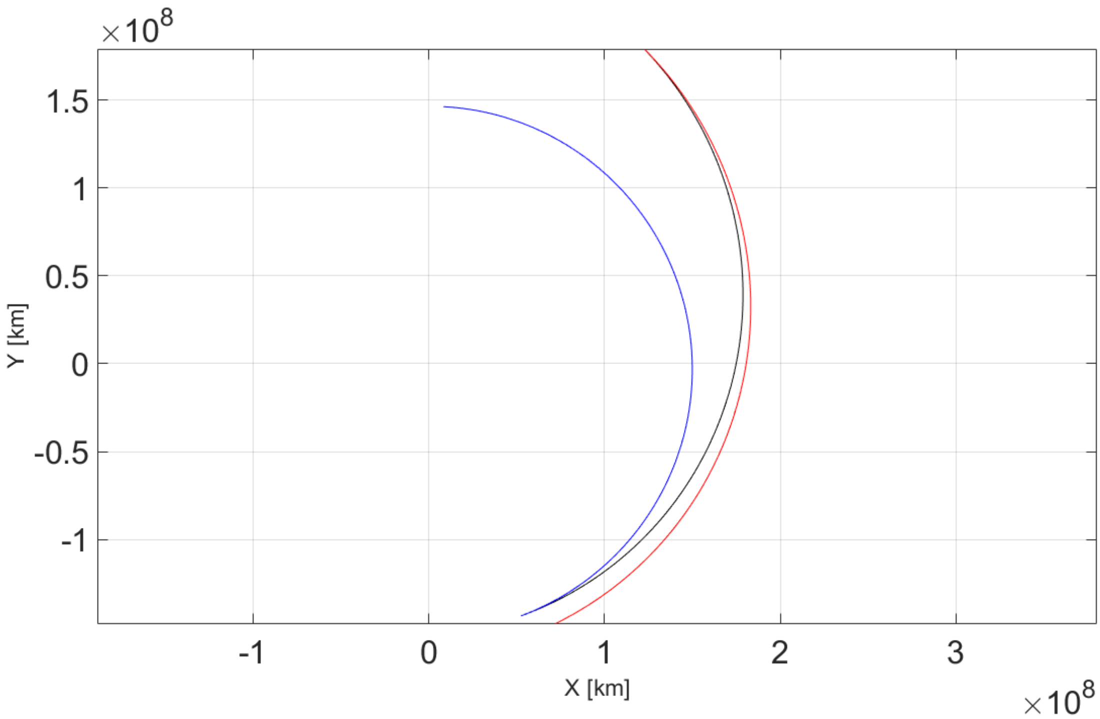

Figure C.20: 253062 (2002 TC_{70})

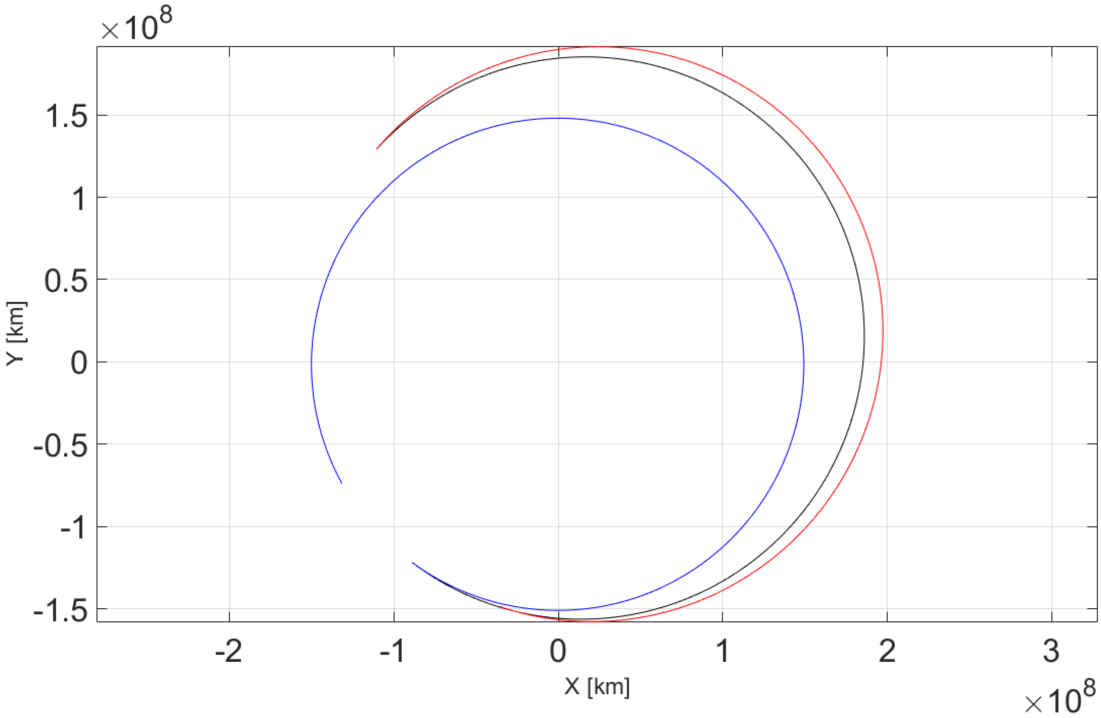

Figure C.21: — (2011 CG_2

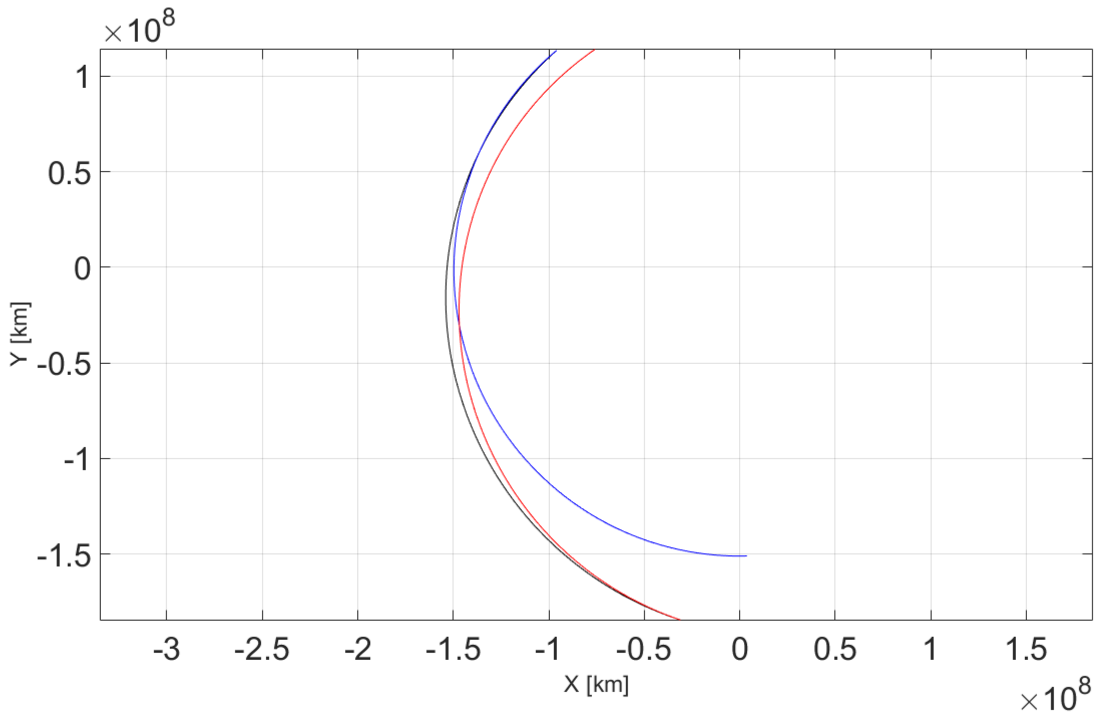

Figure C.22: — (2001 QC_{34})

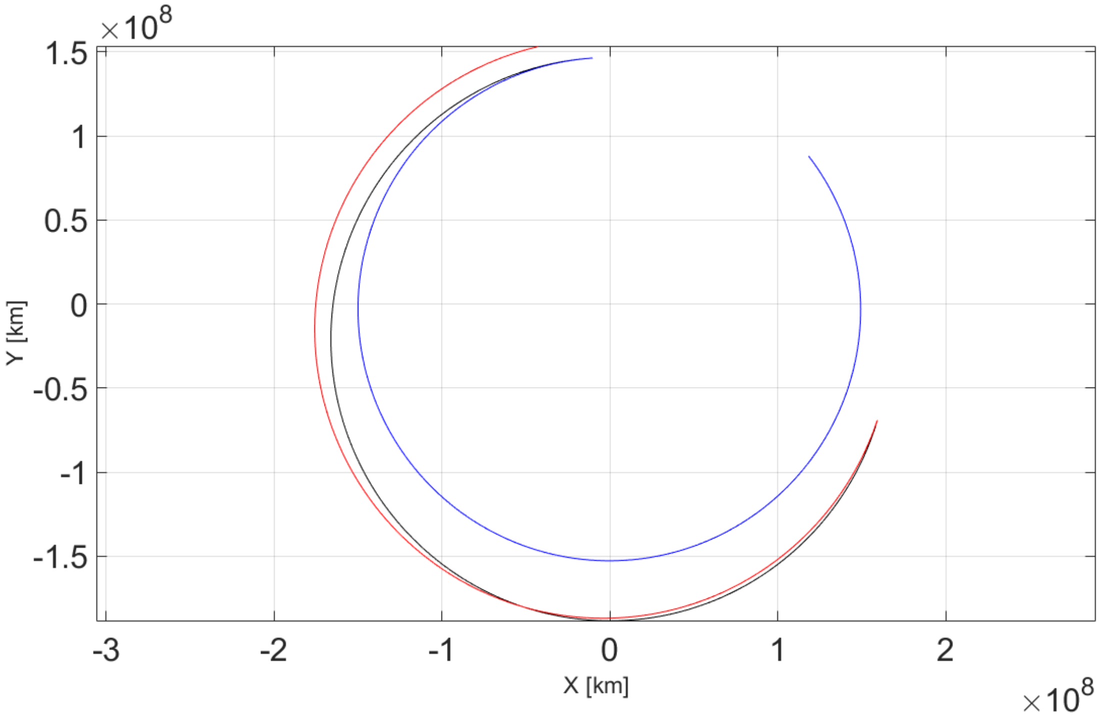

Figure C.23: — (2013 PA_7)

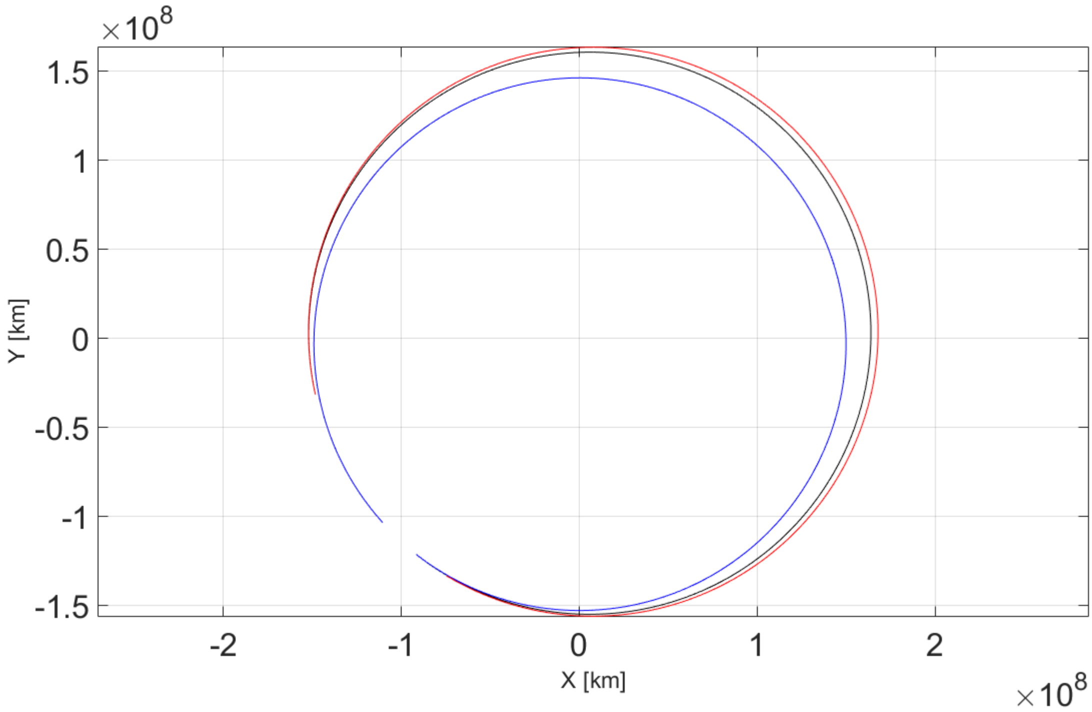

Figure C.24: — (2008 HU_4)

C.3 Lambert's Problem NSGA-II Plots

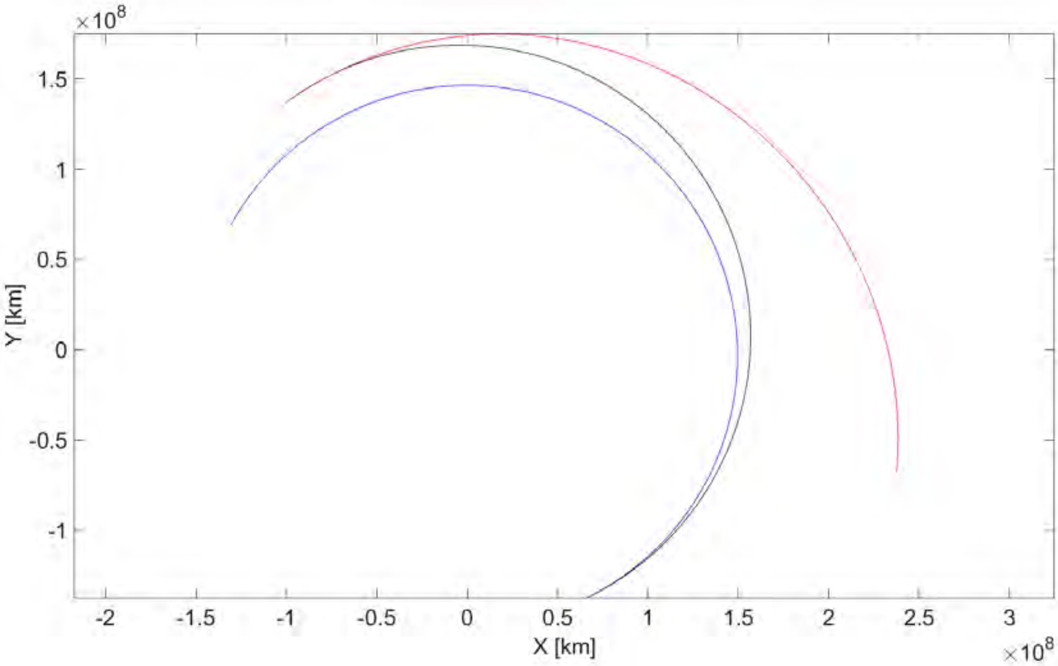

Figure C.25: 433 Eros (1898 DQ)

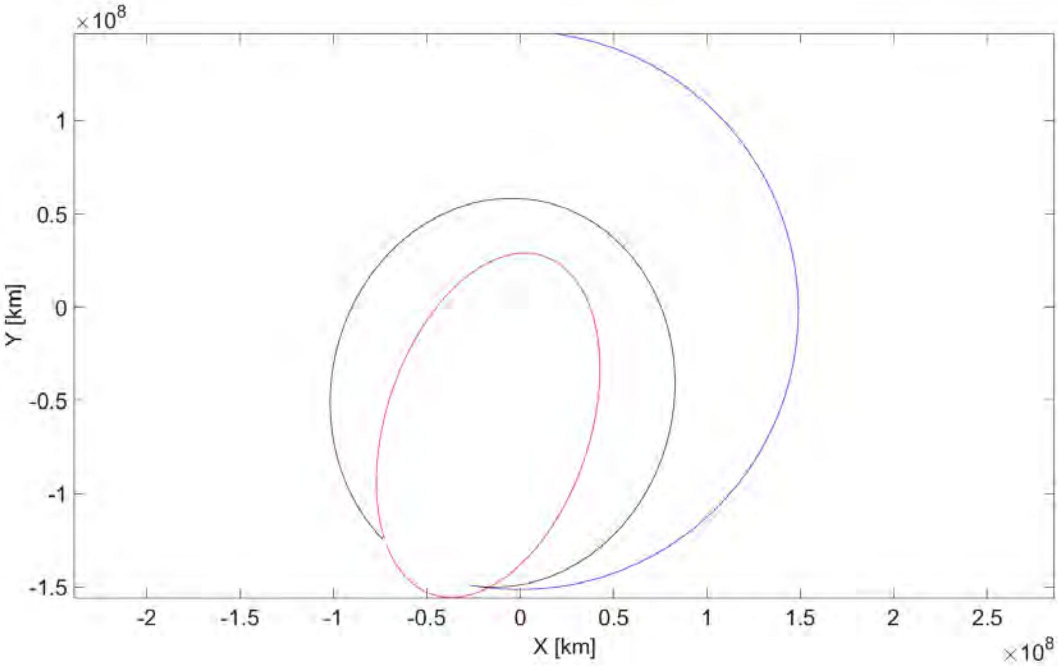

Figure C.26: 66391 (1999 KW_4)

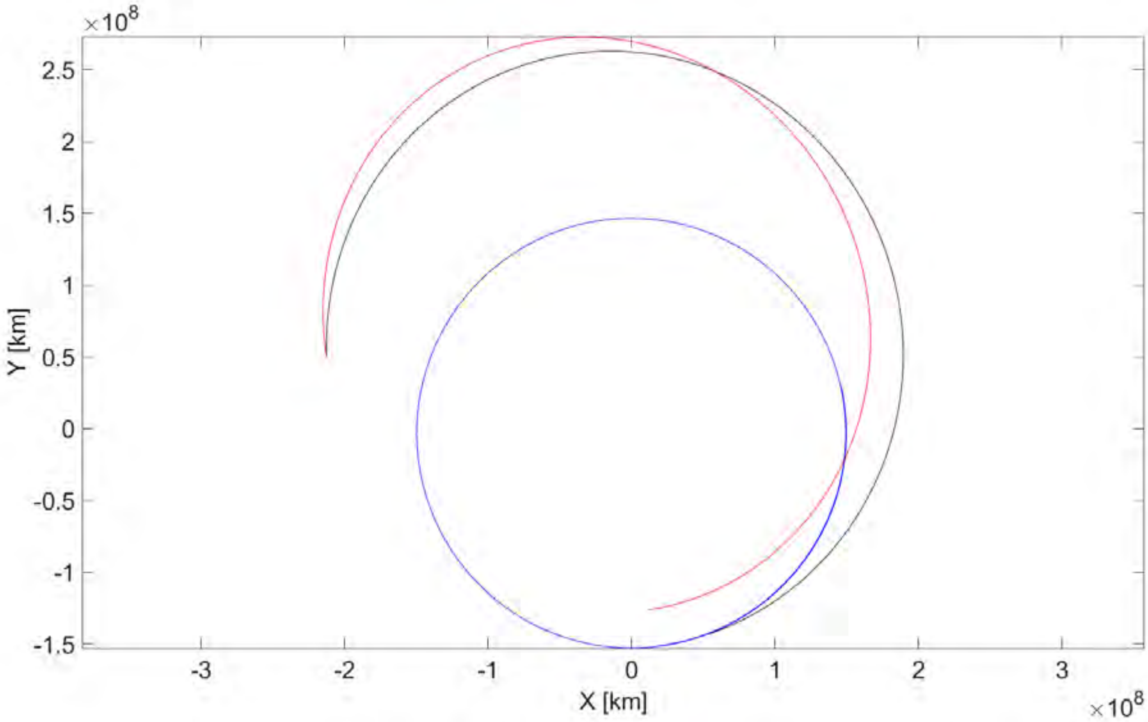

Figure C.27: 185851 (2000 DP_{107})

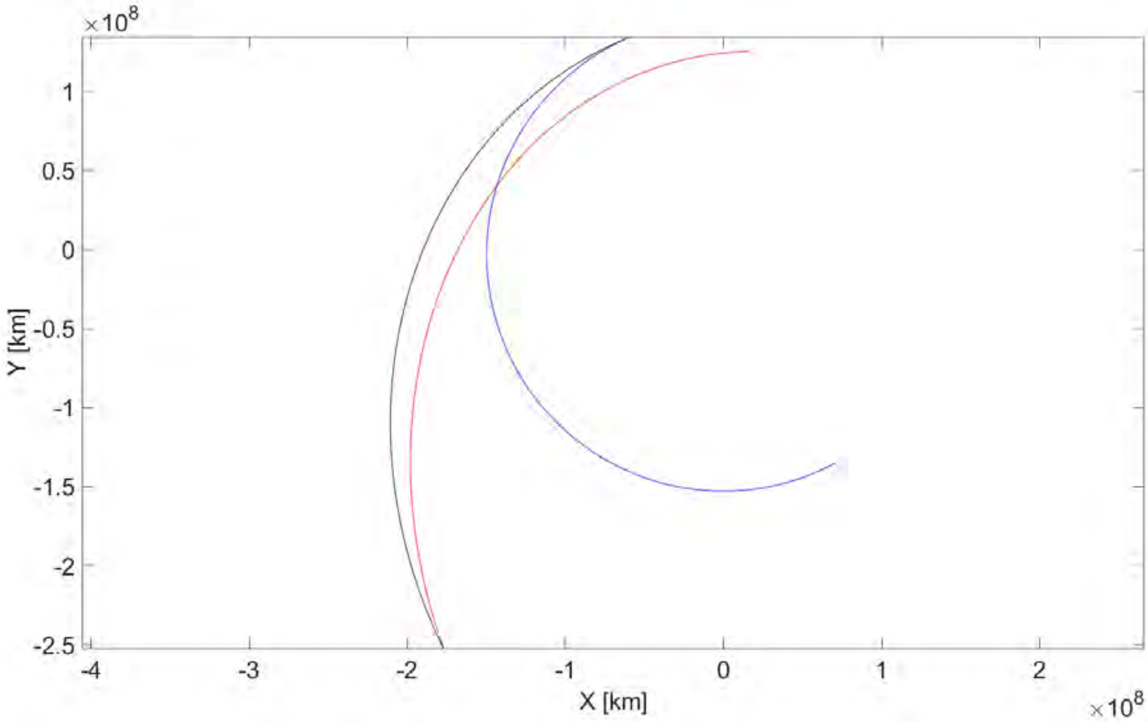

Figure C.28: 494658 (2000 UG_{11})

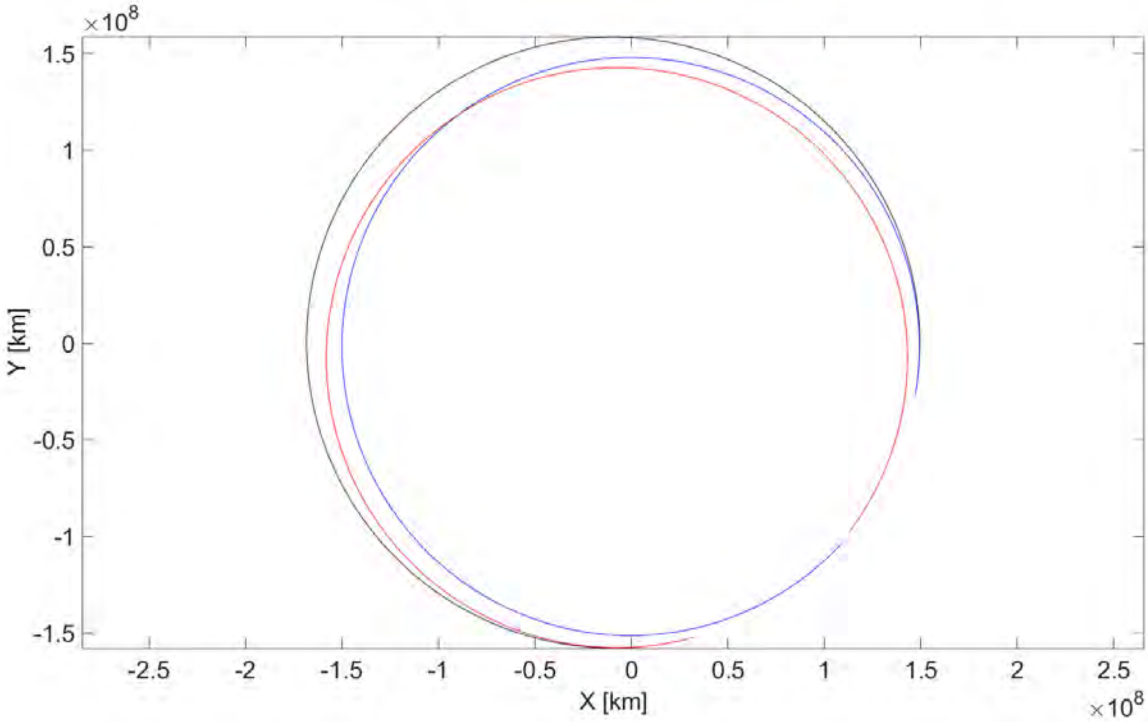

Figure C.29: 459872(2014 EK_{24})

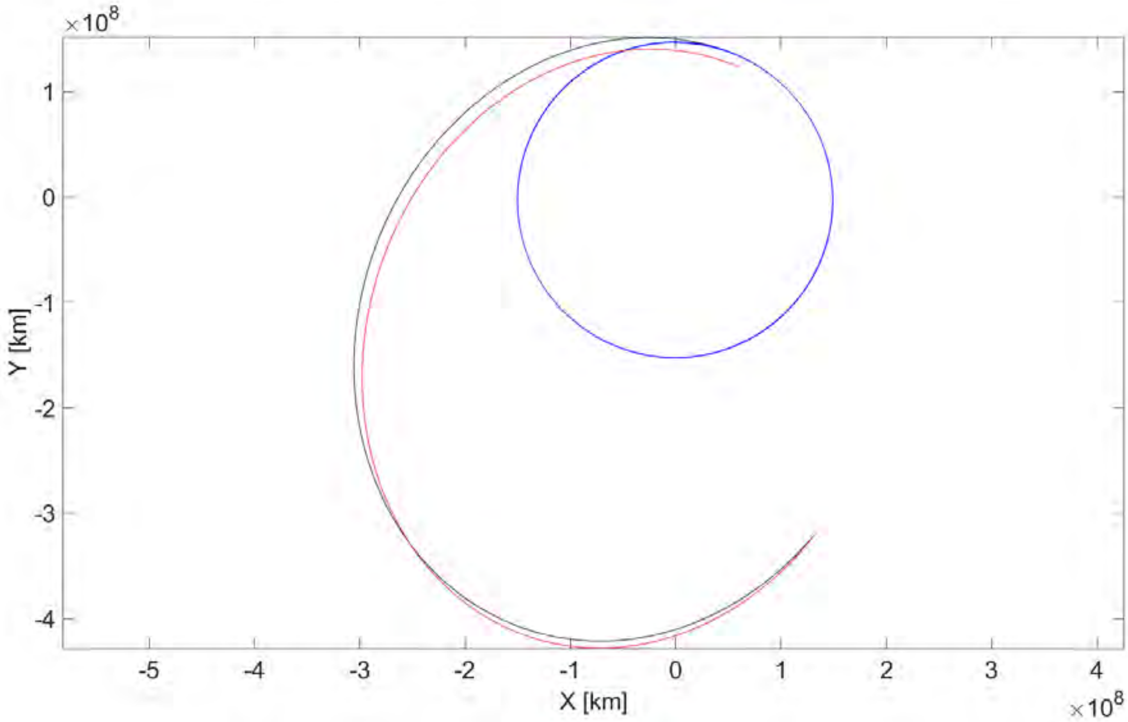

Figure C.30: — (2014 SC_{324})

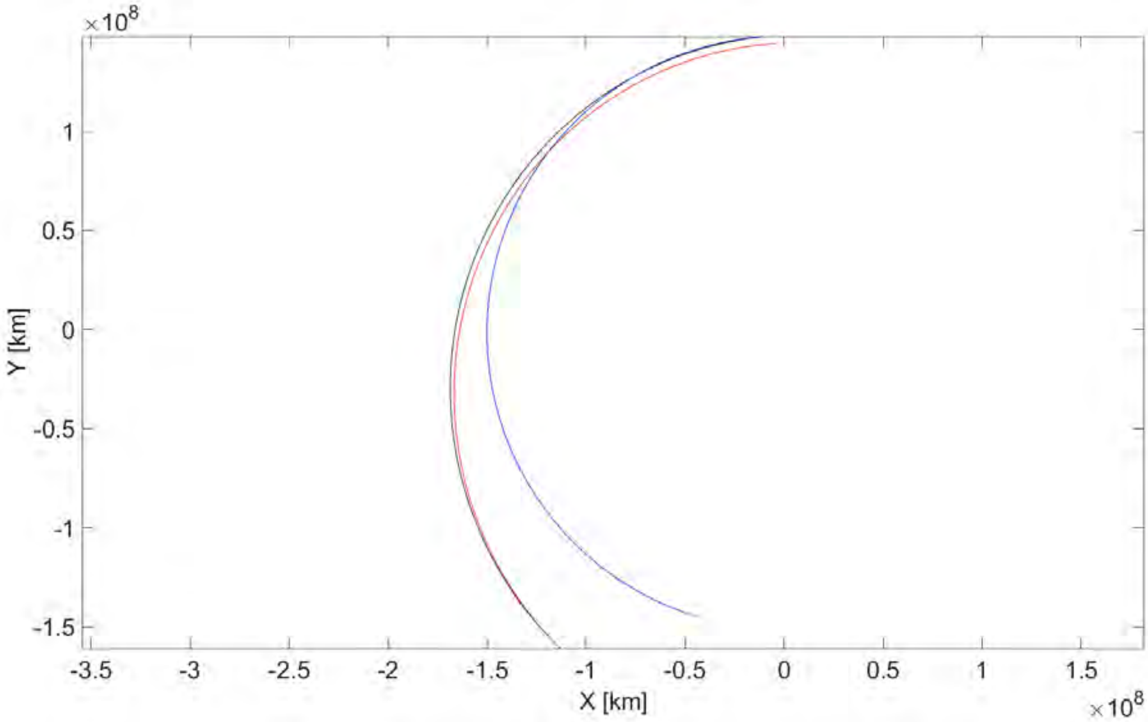

Figure C.31: 162173 Ryugu (1999 JU_3)

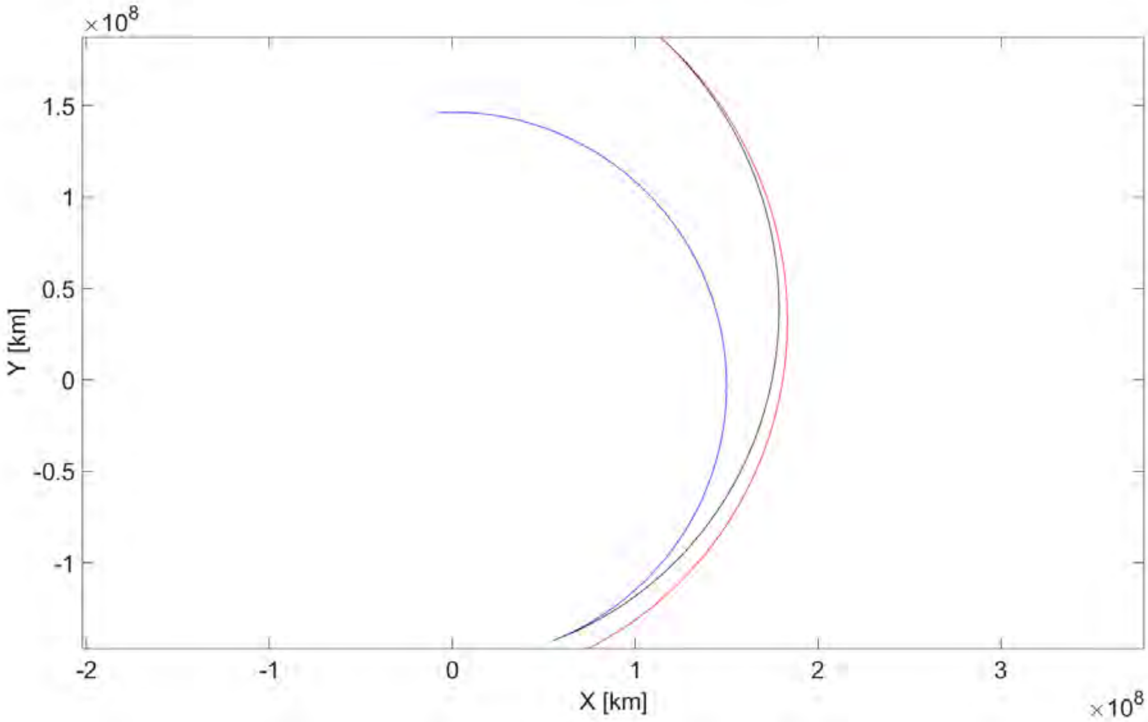

Figure C.32: 253062 (2002 TC_{70})

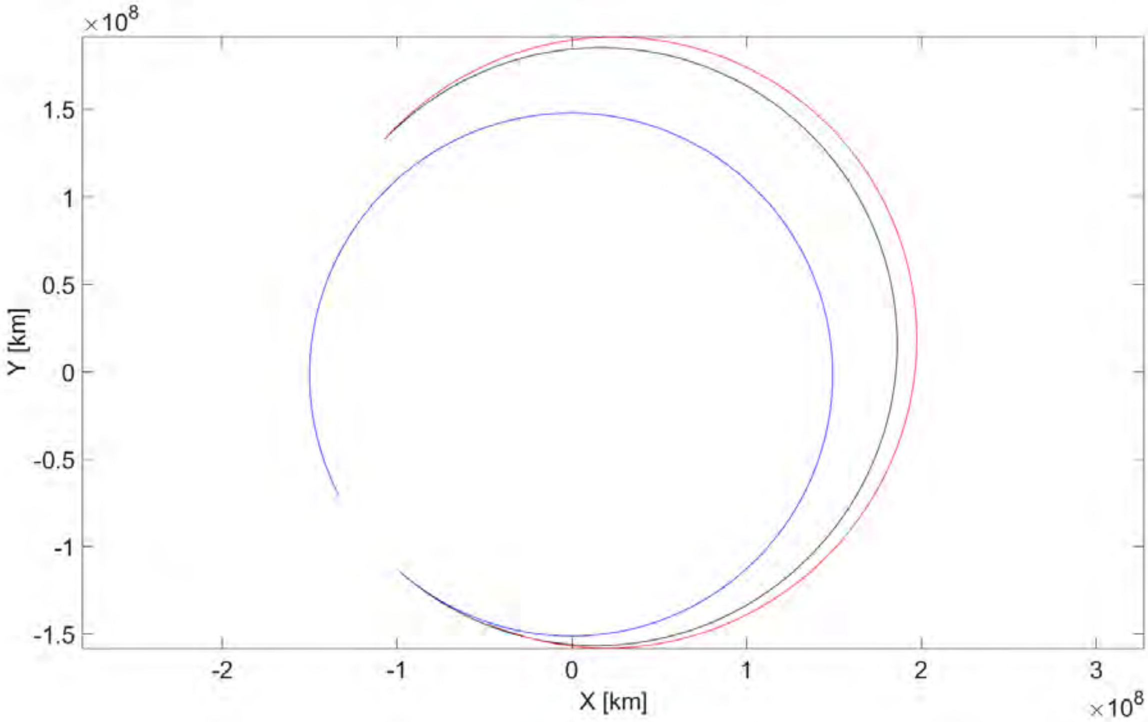

Figure C.33: — (2011 CG_2

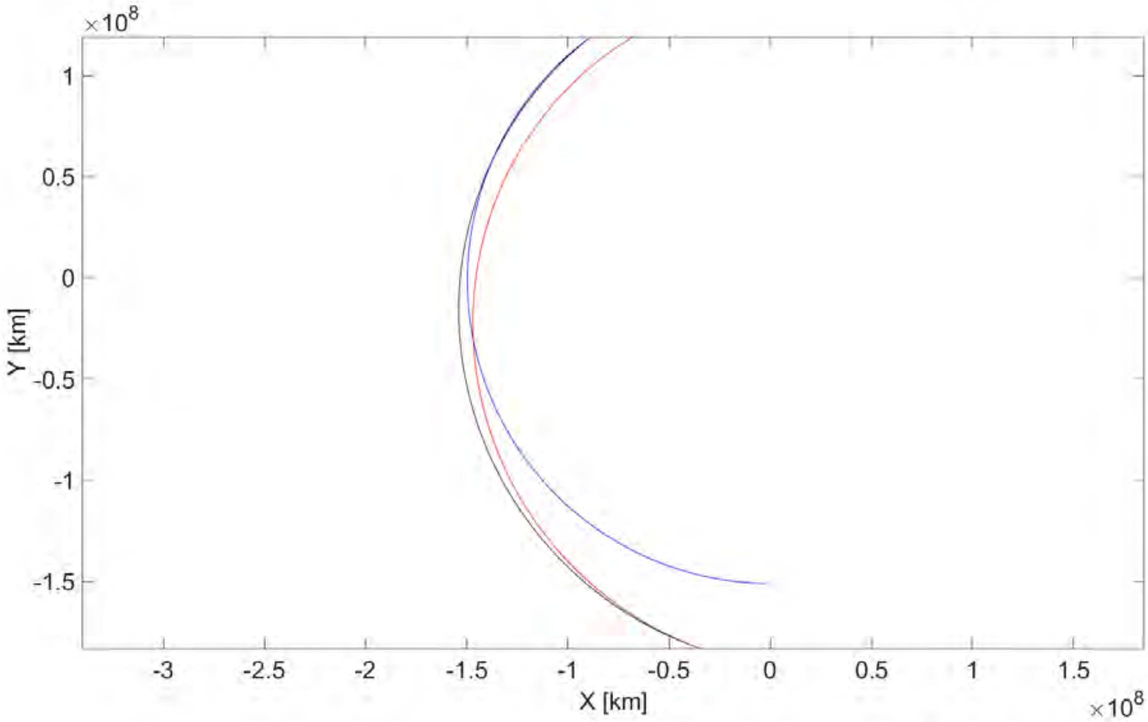

Figure C.34: — (2001 QC_{34})

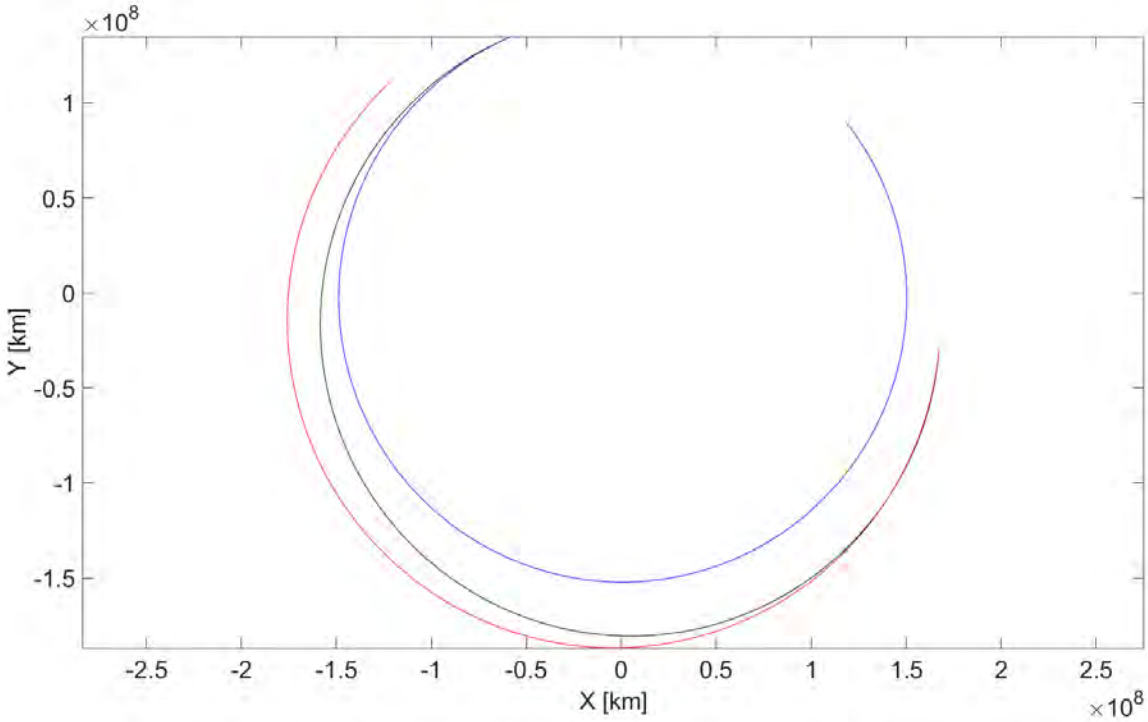

Figure C.35: — (2013 PA_7)

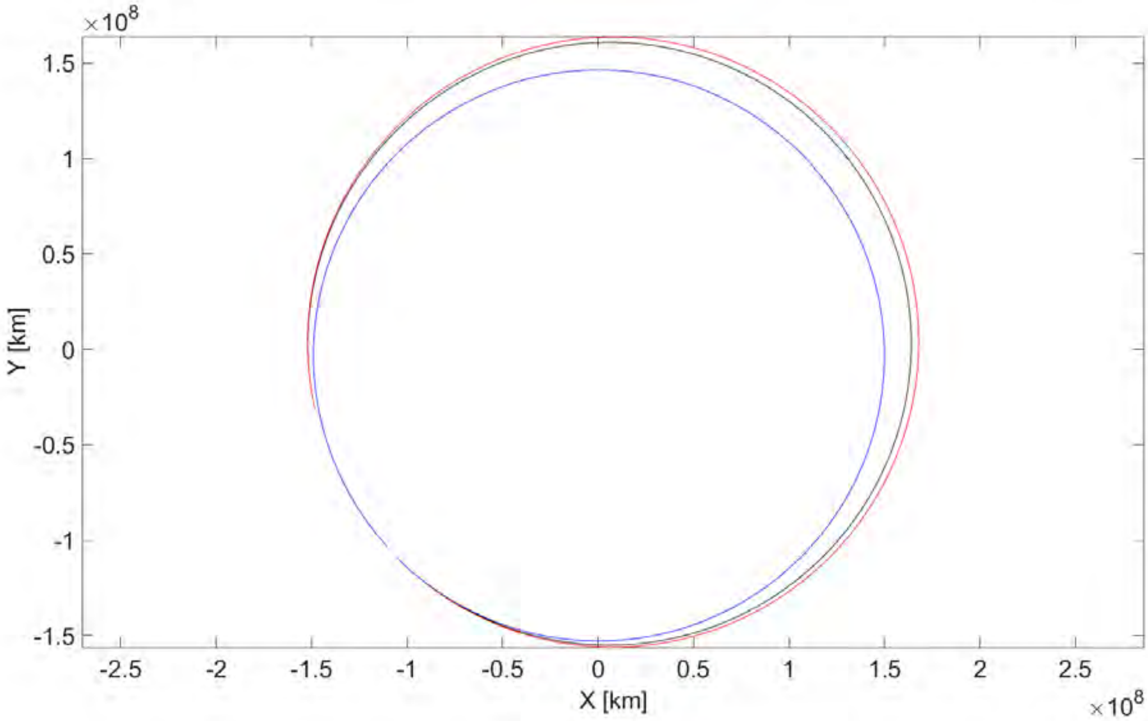

Figure C.36: — (2008 HU_4)

C.4 Flyby Transfer Plots

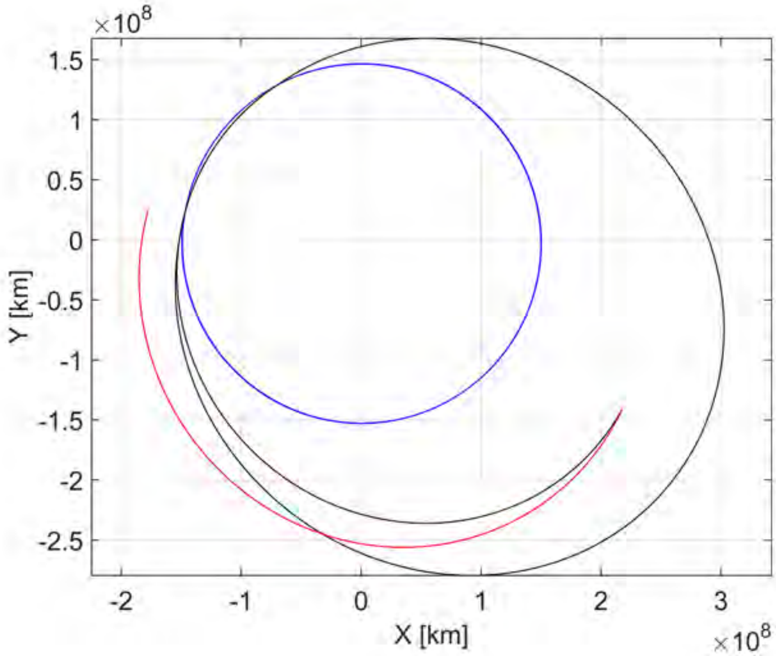

Figure C.37: 433 Eros (1898 DQ)

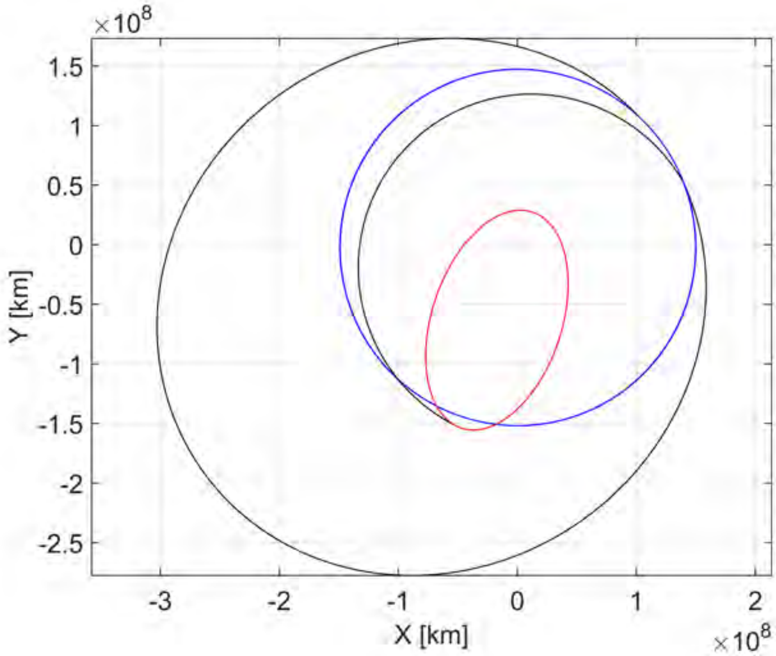

Figure C.38: 66391 (1999 KW_4)

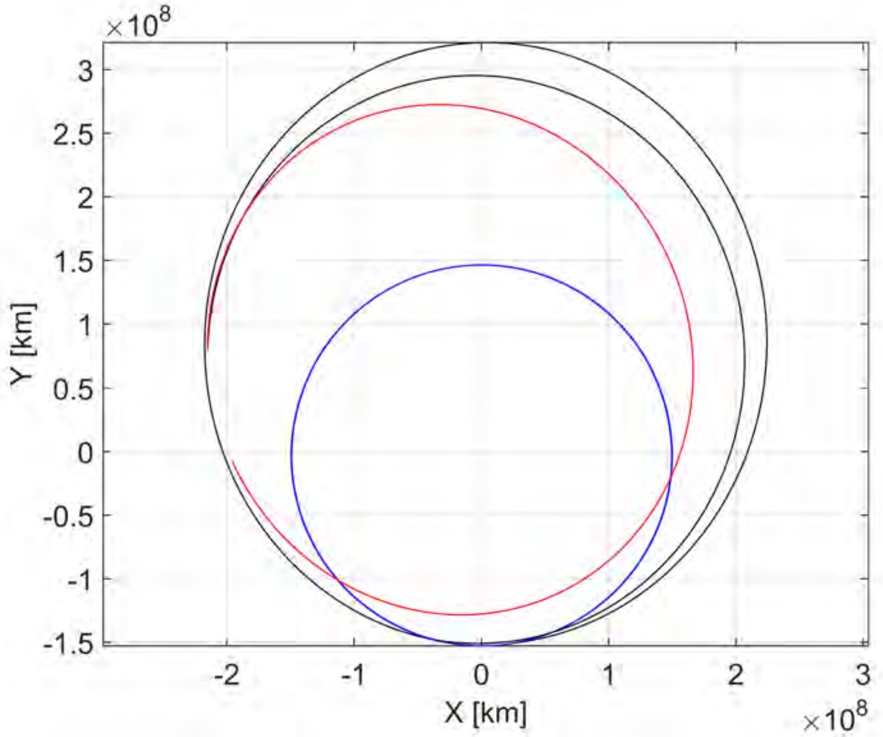

Figure C.39: 185851 (2000 DP_{107})

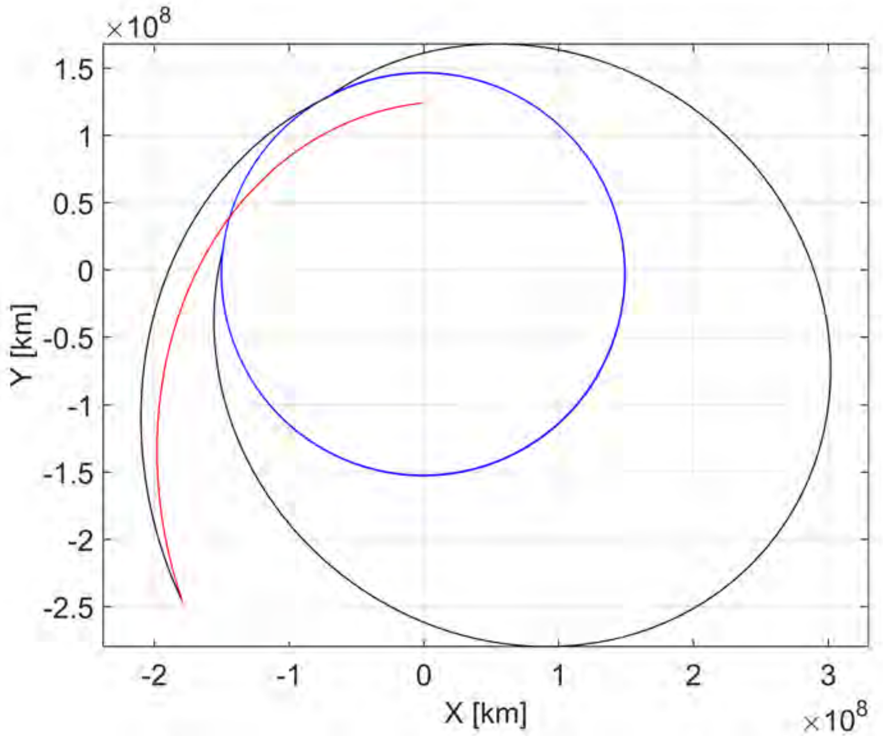

Figure C.40: 494658 (2000 UG_{11})

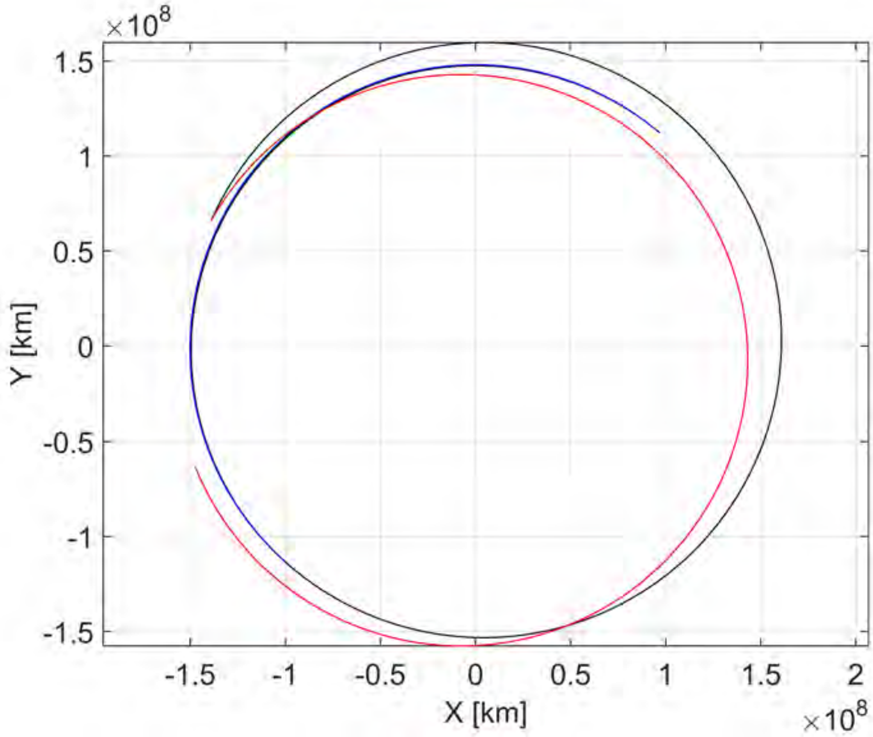

Figure C.41: 459872(2014 EK_{24})

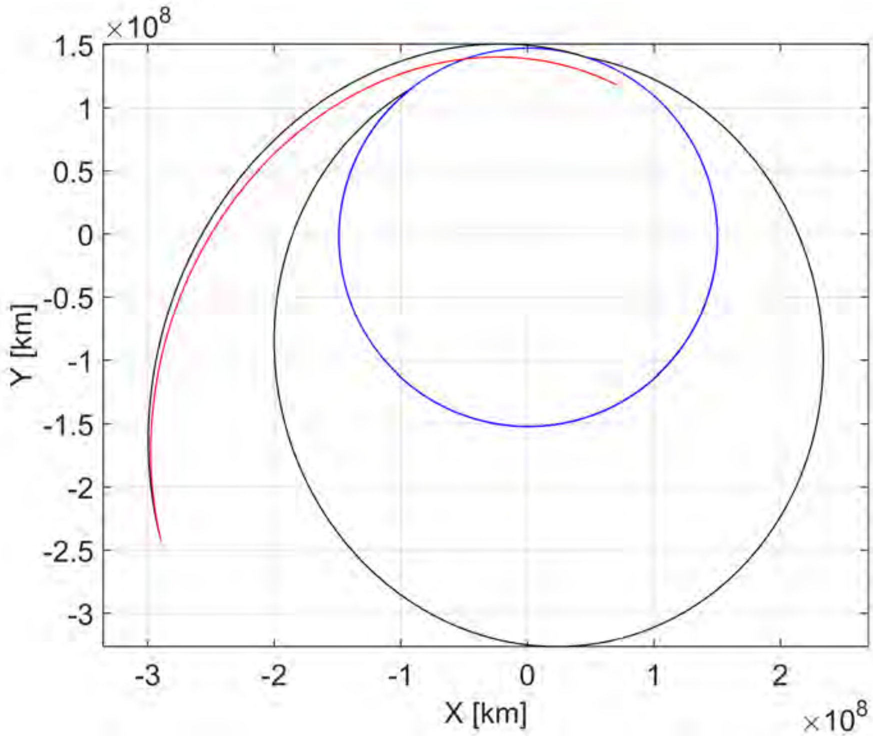

Figure C.42: — (2014 SC_{324})

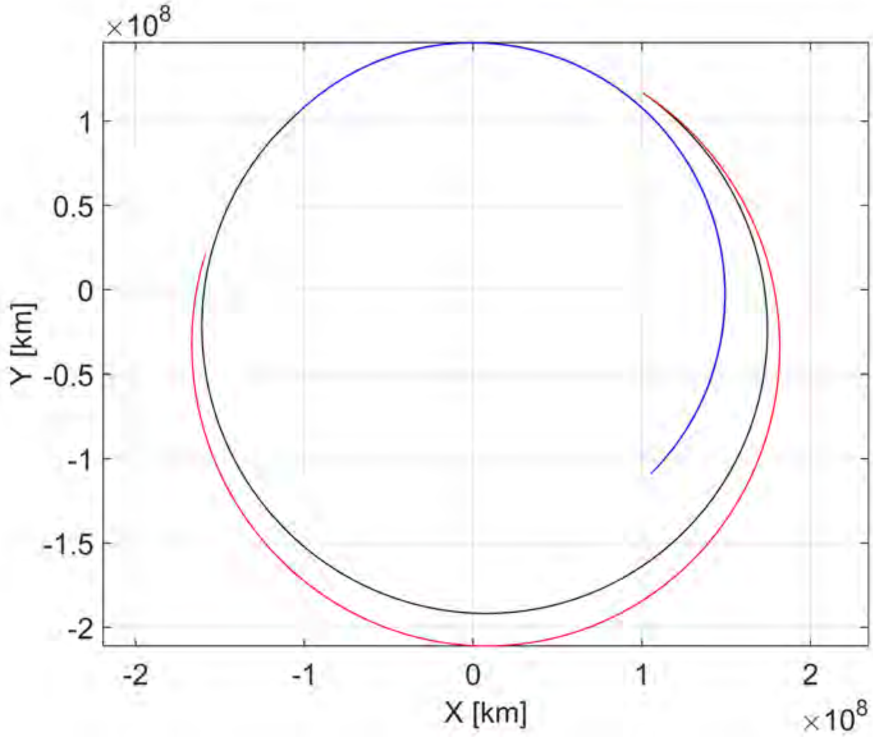

Figure C.43: 162173 Ryugu (1999 JU_3)

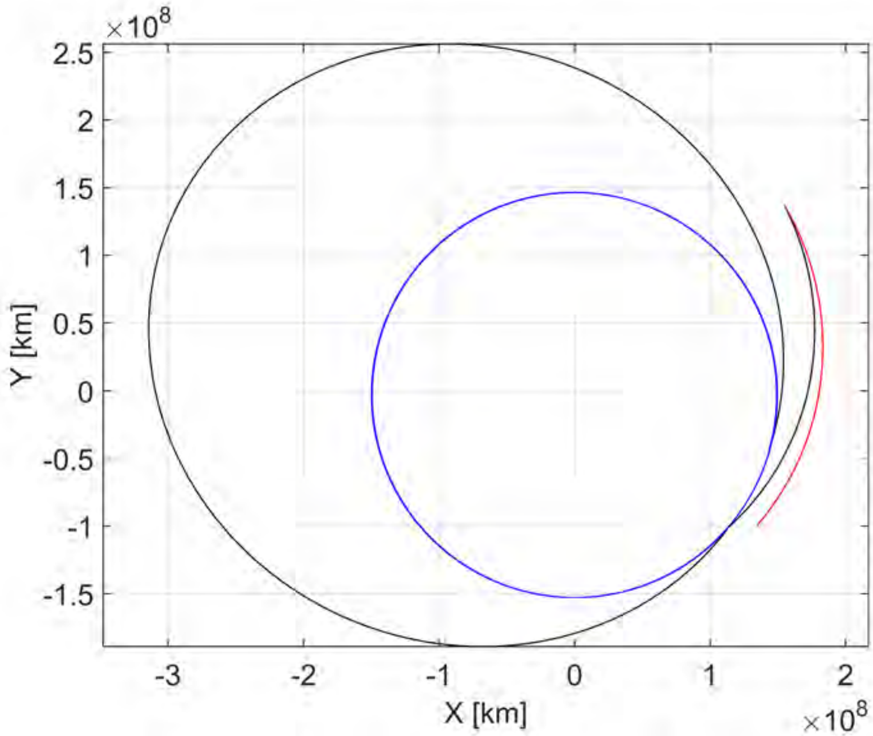

Figure C.44: 253062 (2002 TC_{70})

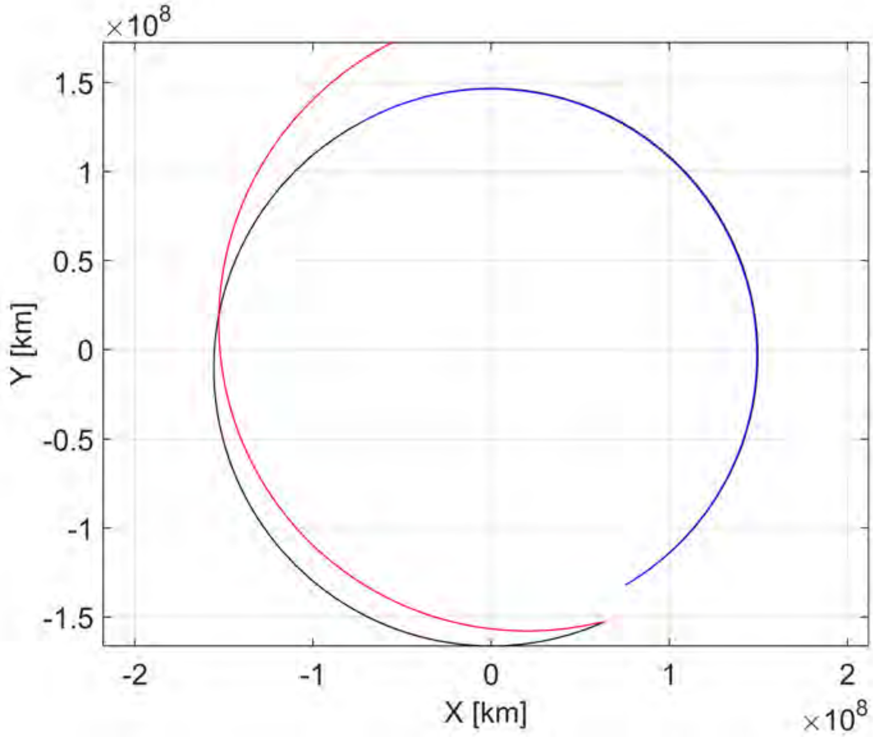

Figure C.45: — (2011 CG_2)

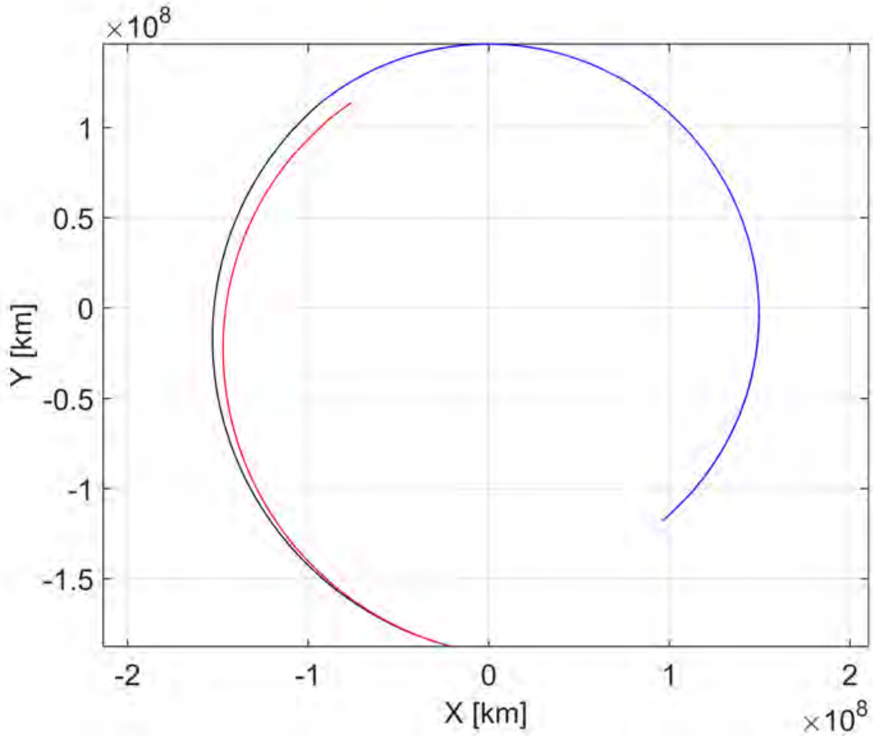

Figure C.46: — (2001 QC_{34})

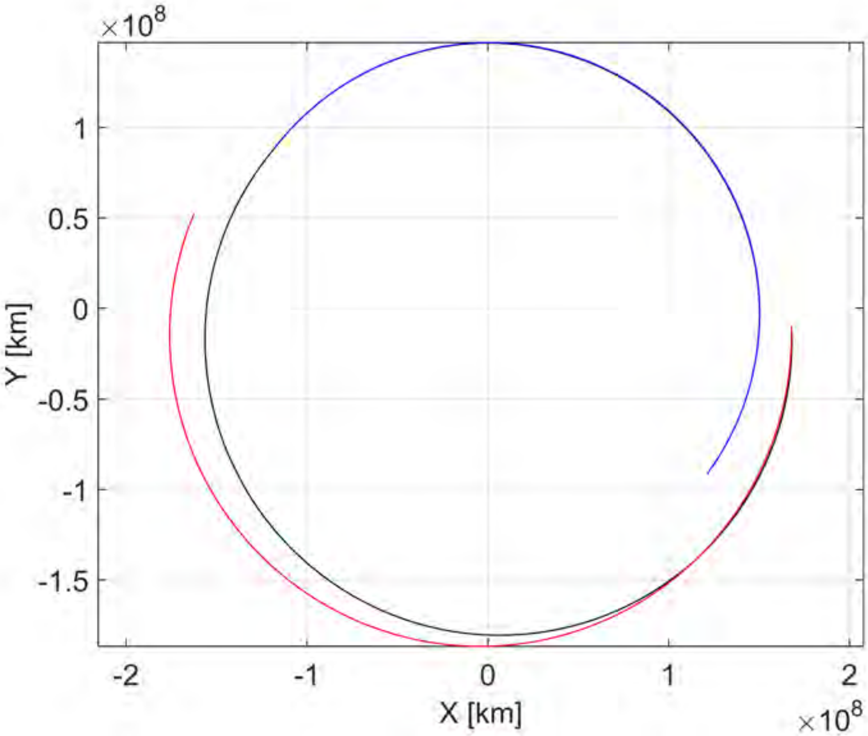

Figure C.47: — (2013 PA_7)

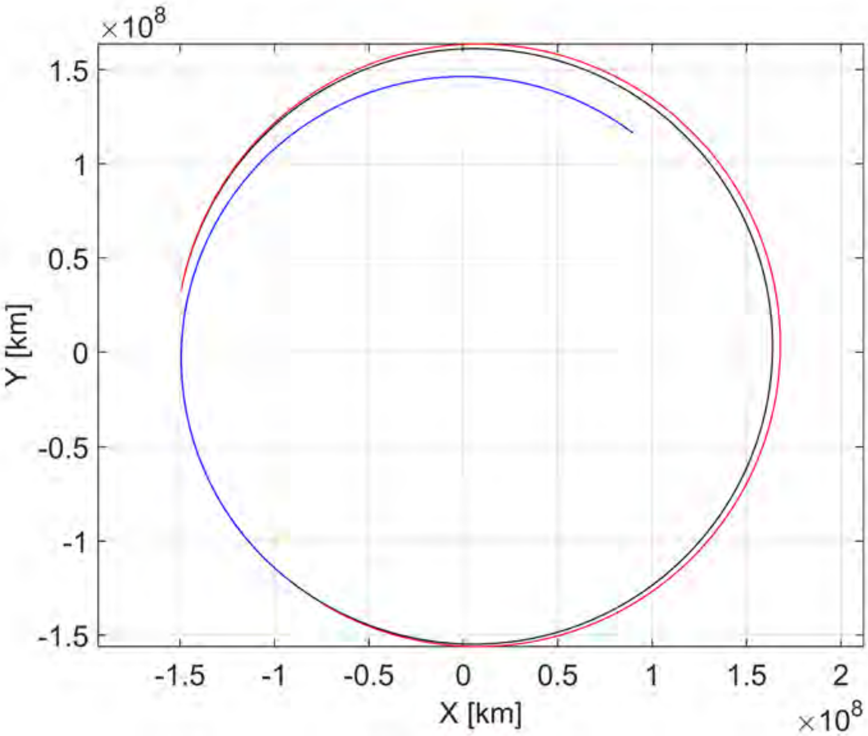

Figure C.48: — (2008 HU_4)

C.5 Flyby Transfer NSGA-II Plots. $N_{generations} = 200$.

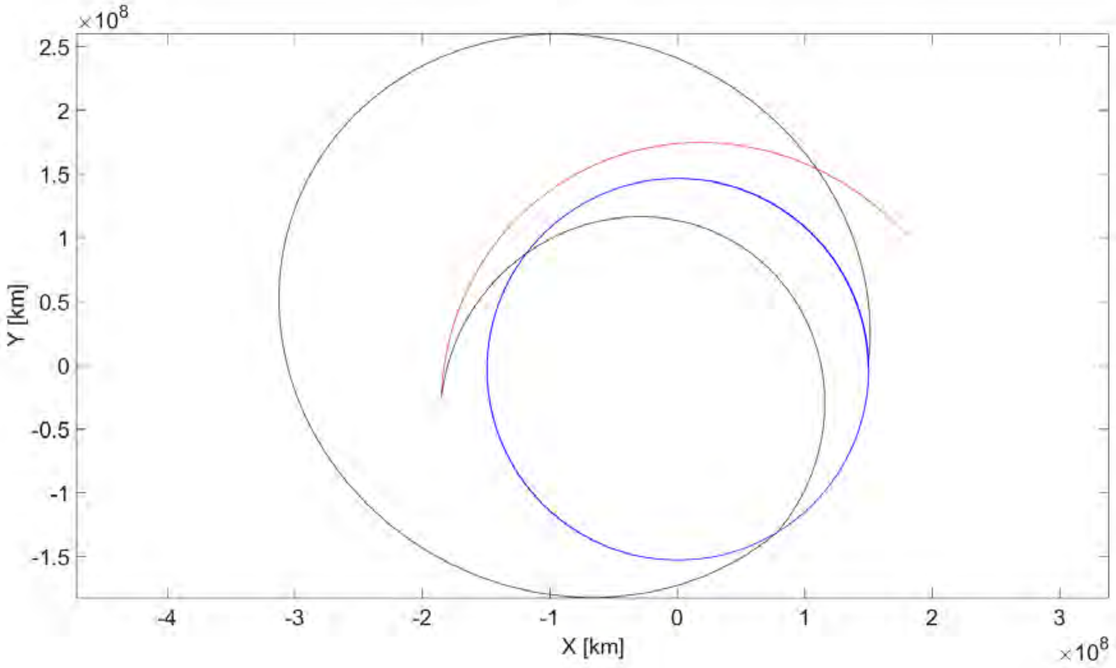

Figure C.49: 433 Eros (1898 DQ)

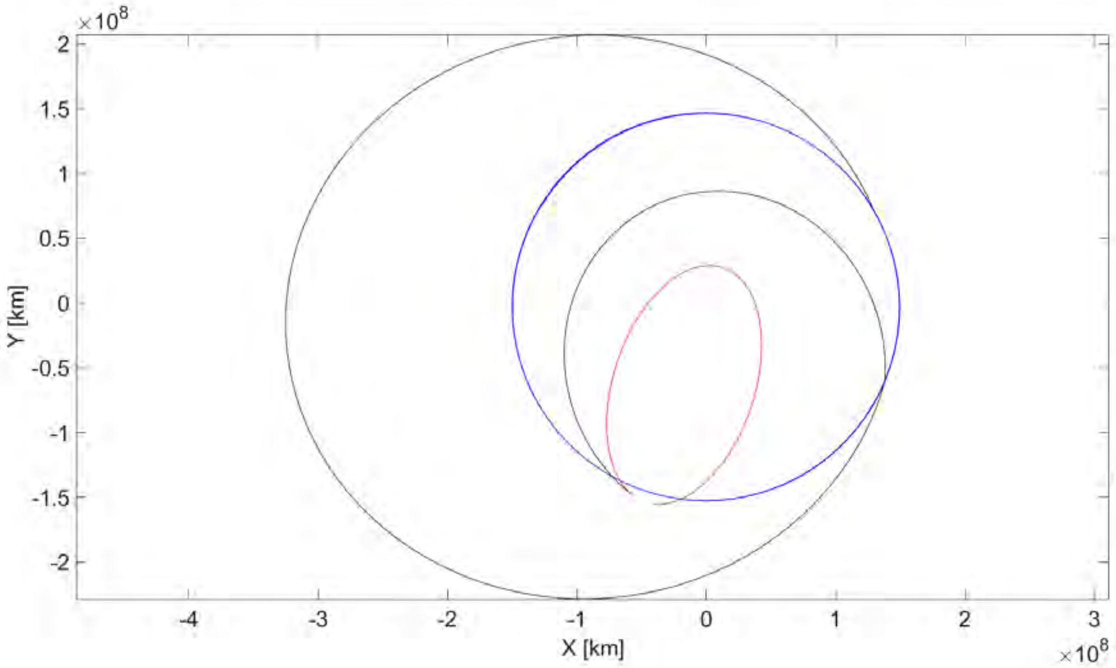

Figure C.50: 66391 (1999 KW_4)

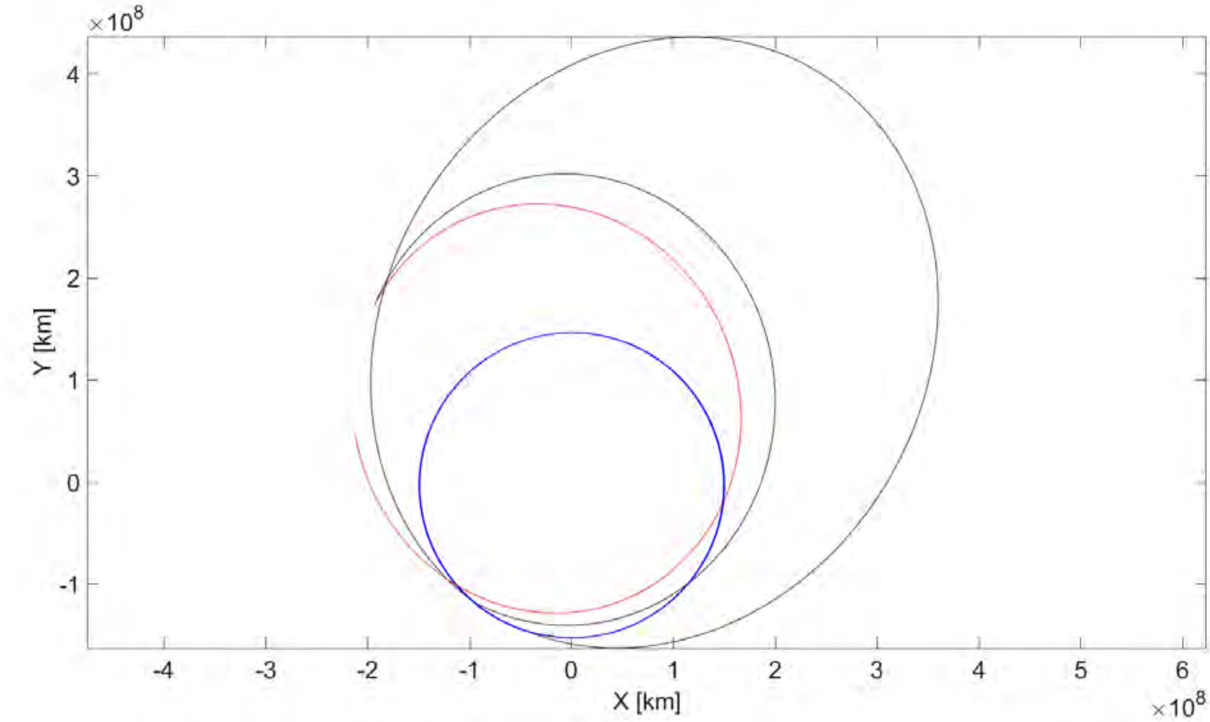

Figure C.51: 185851 (2000 DP_{107})

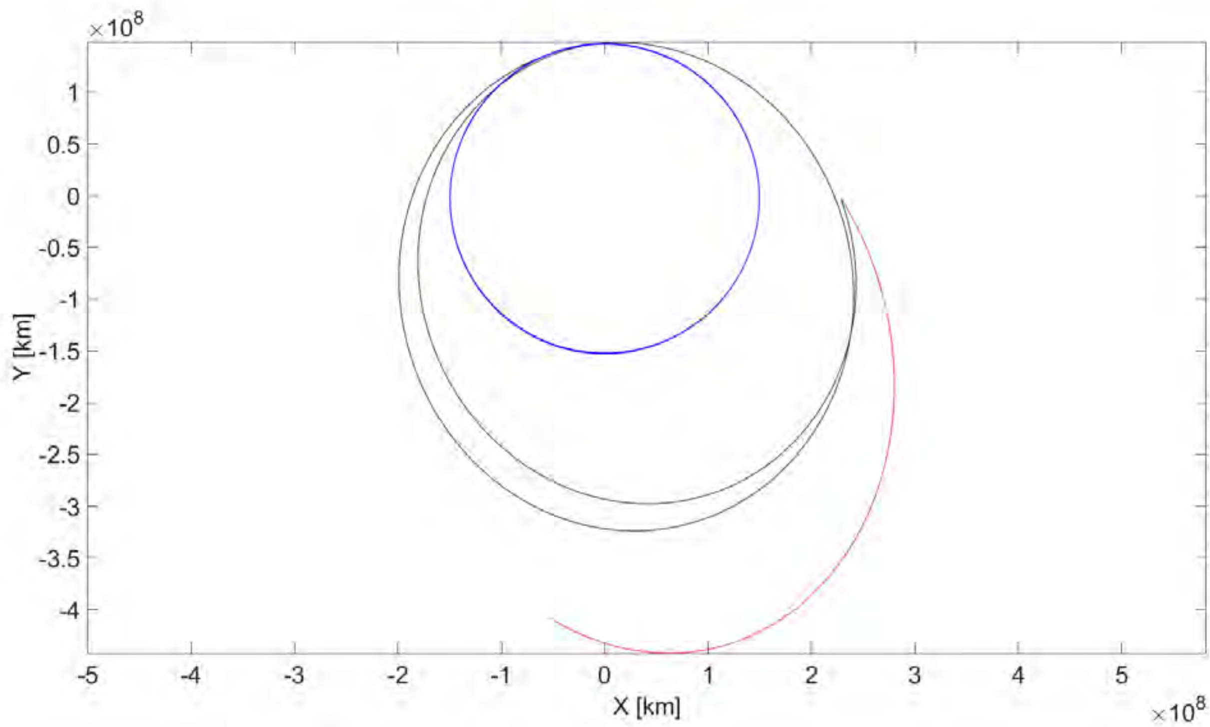

Figure C.52: 494658 (2000 UG_{11})

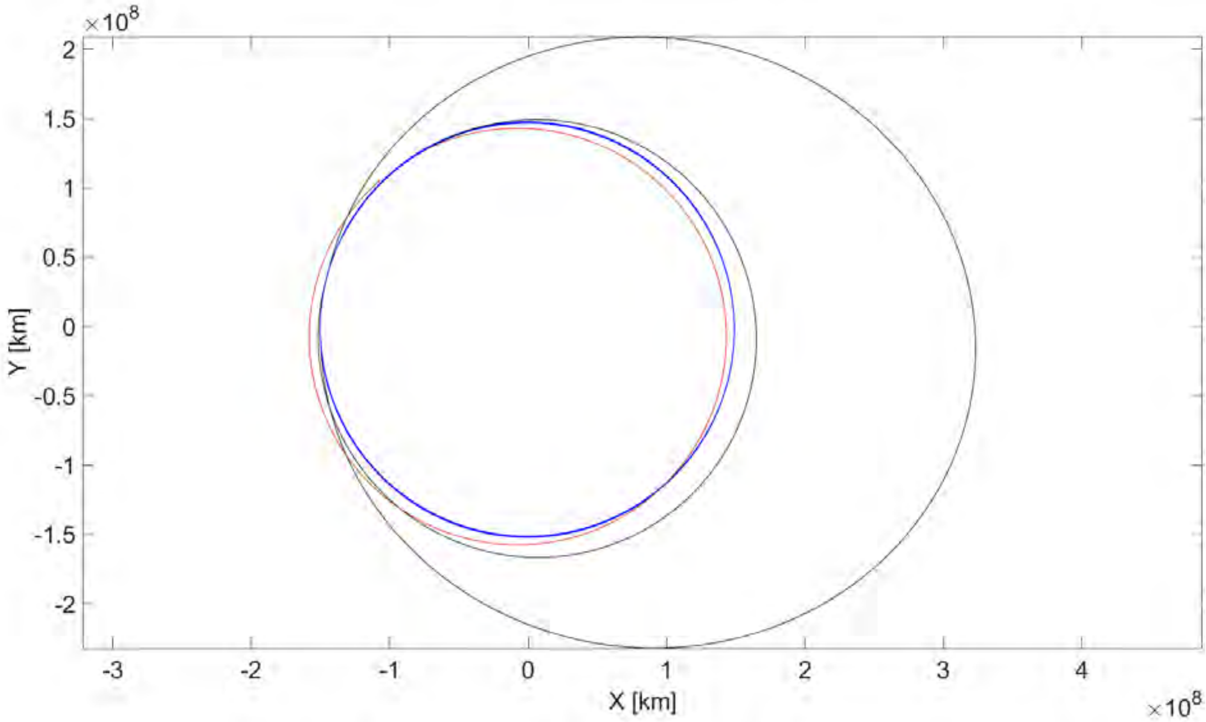

Figure C.53: — (2014 EK_{24})

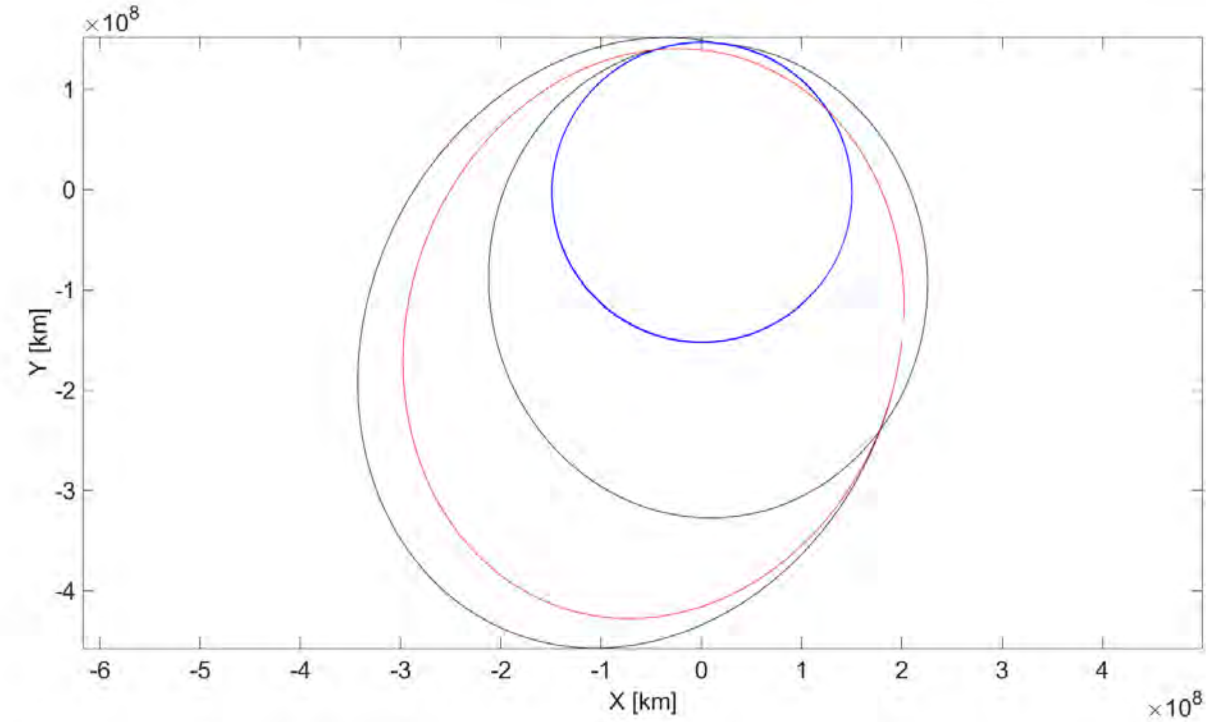

Figure C.54: — (2014 SC_{324})

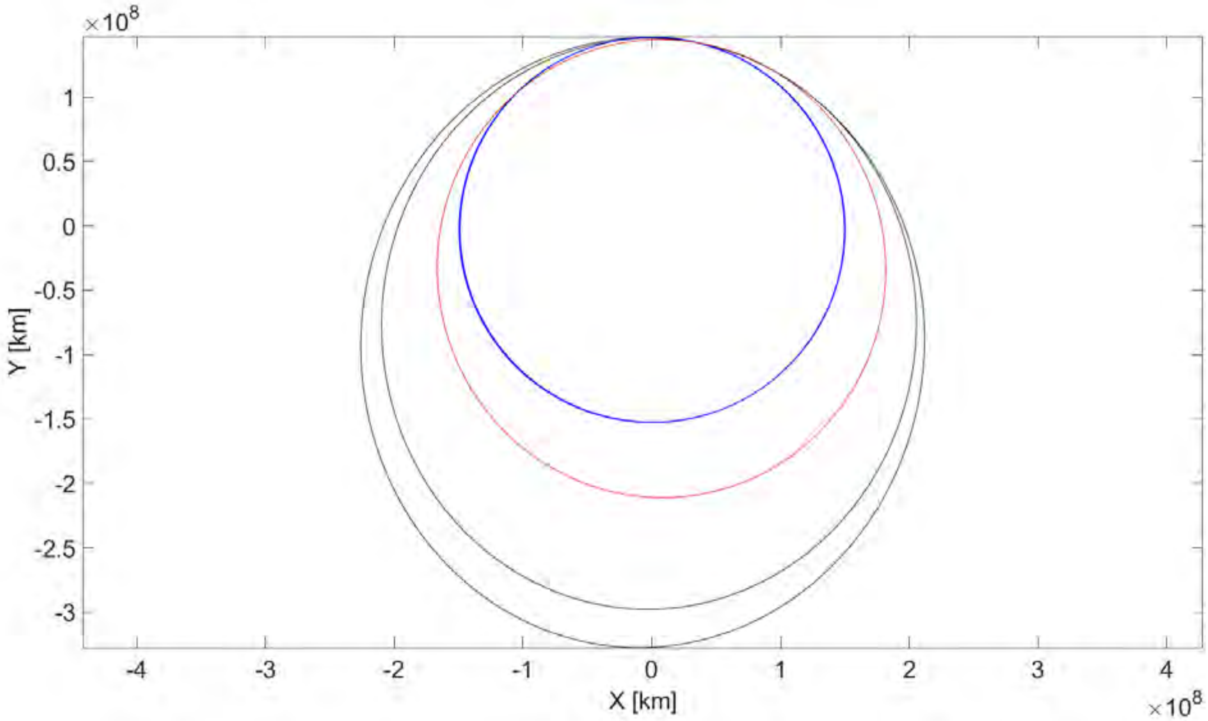

Figure C.55: 162173 Ryugu (1999 JU_3)

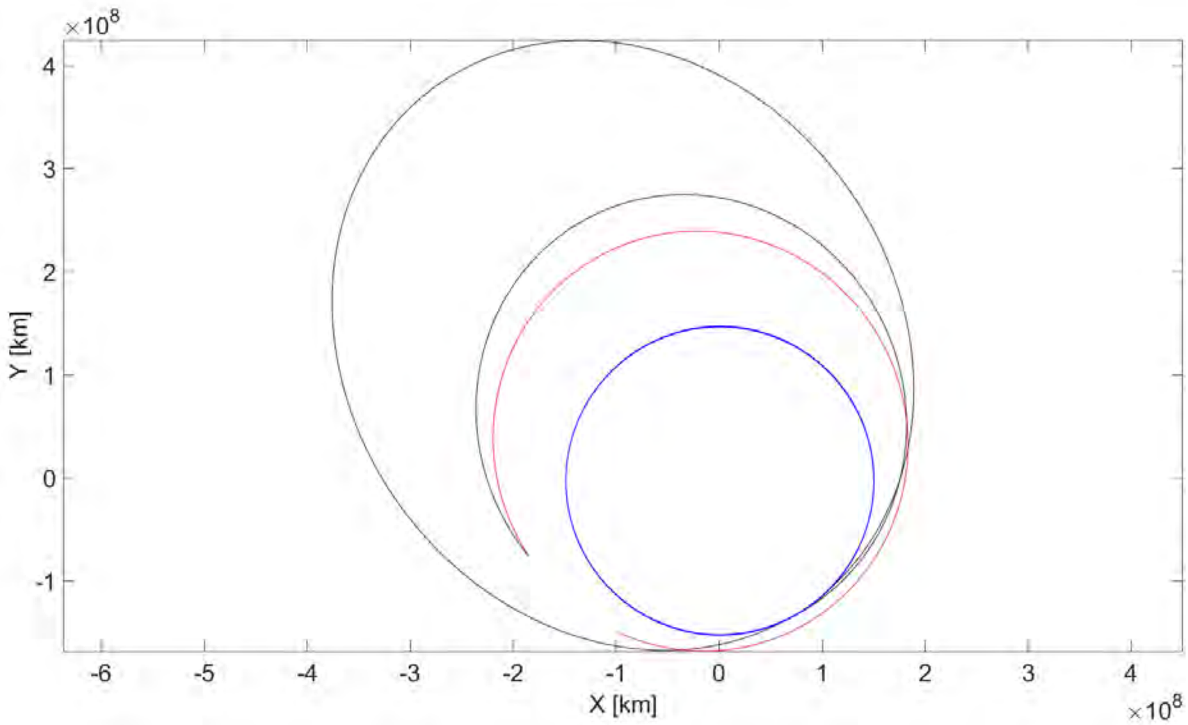

Figure C.56: 253062 (2002 TC_{70})

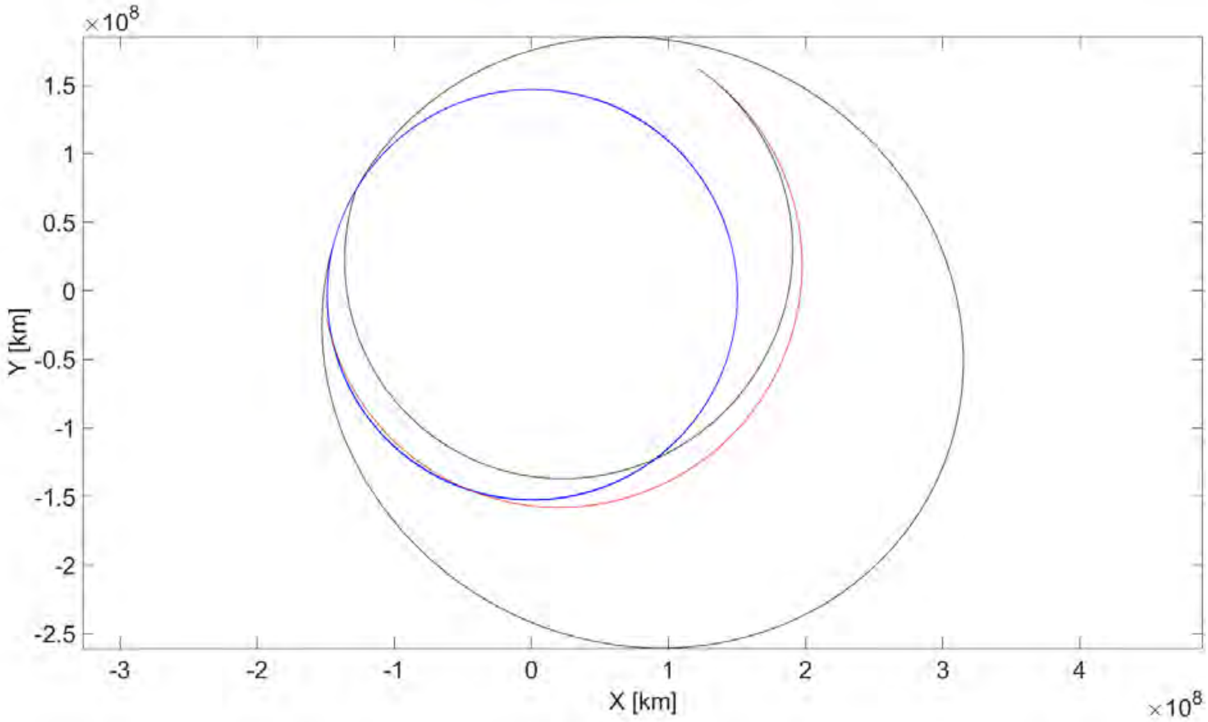

Figure C.57: — (2011 CG_2

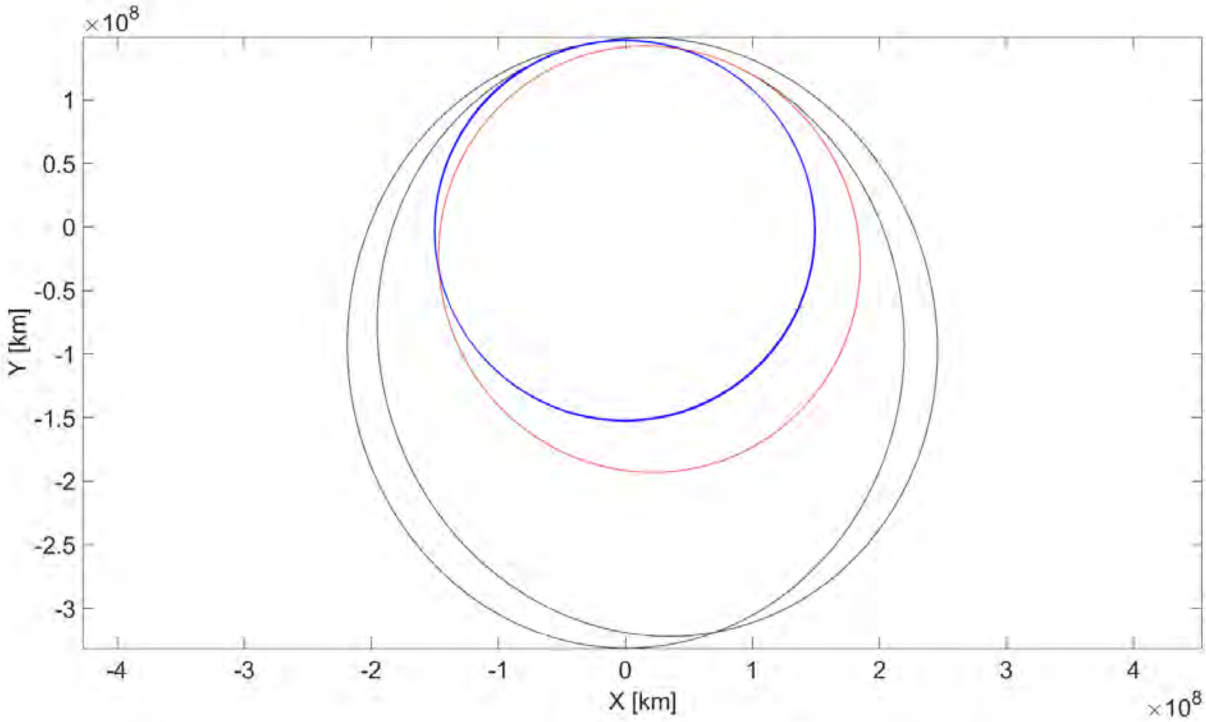

Figure C.58: — (2001 QC_{34})

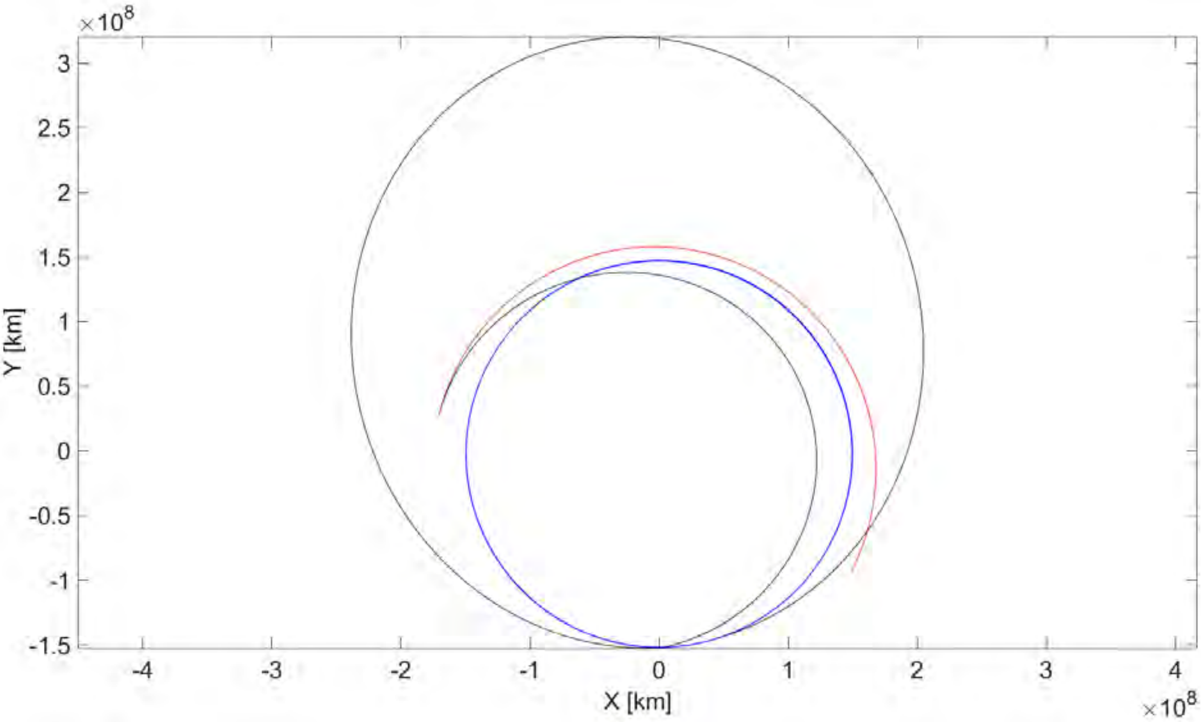

Figure C.59: — (2013 PA_7)

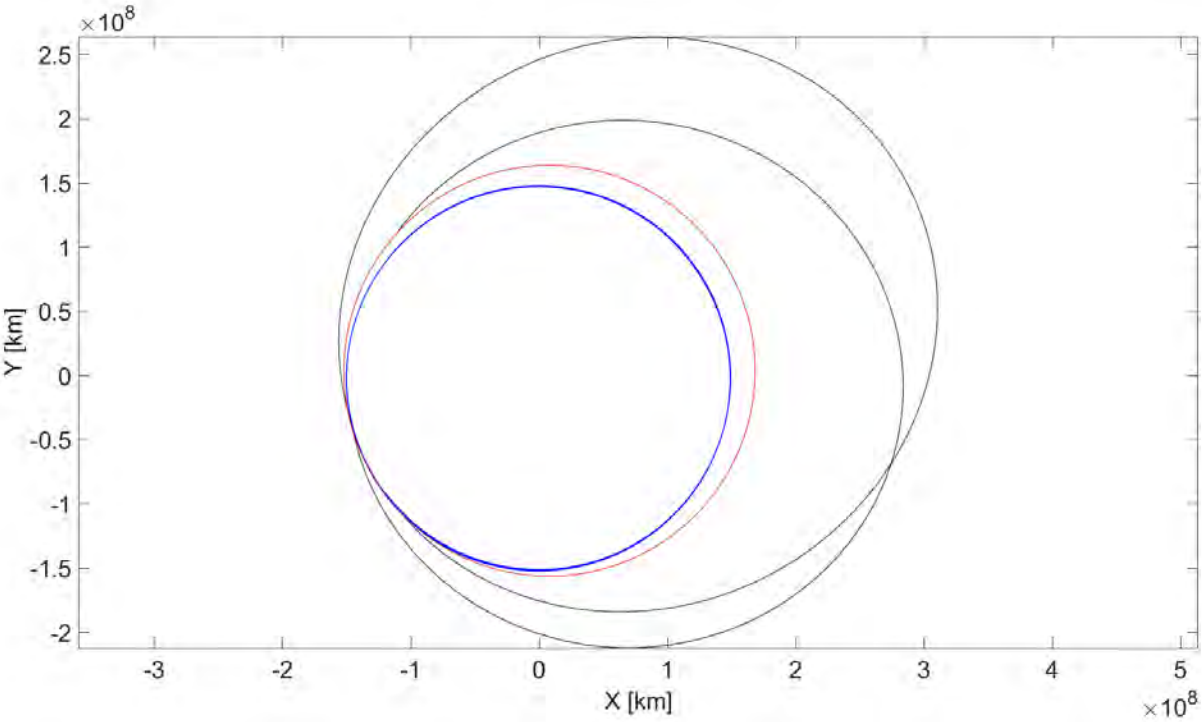

Figure C.60: — (2008 HU_4)

C.6 Flyby Transfer NSGA-II Plots. $N_{generations} = 300$.

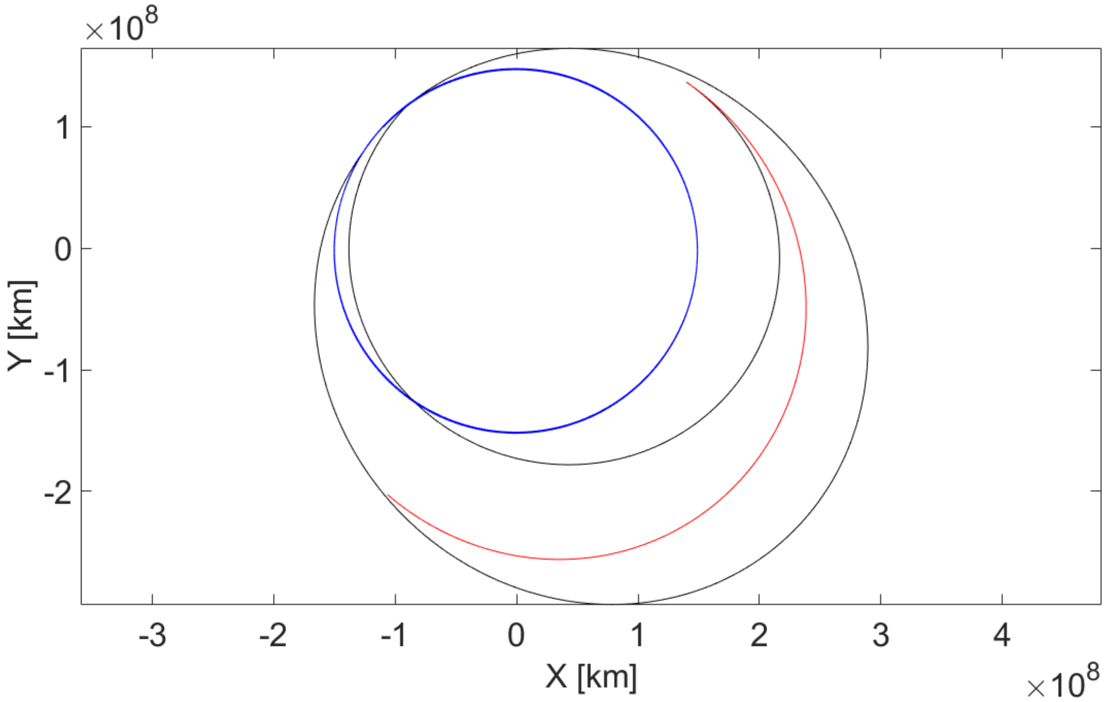

Figure C.61: 433 Eros (1898 DQ)

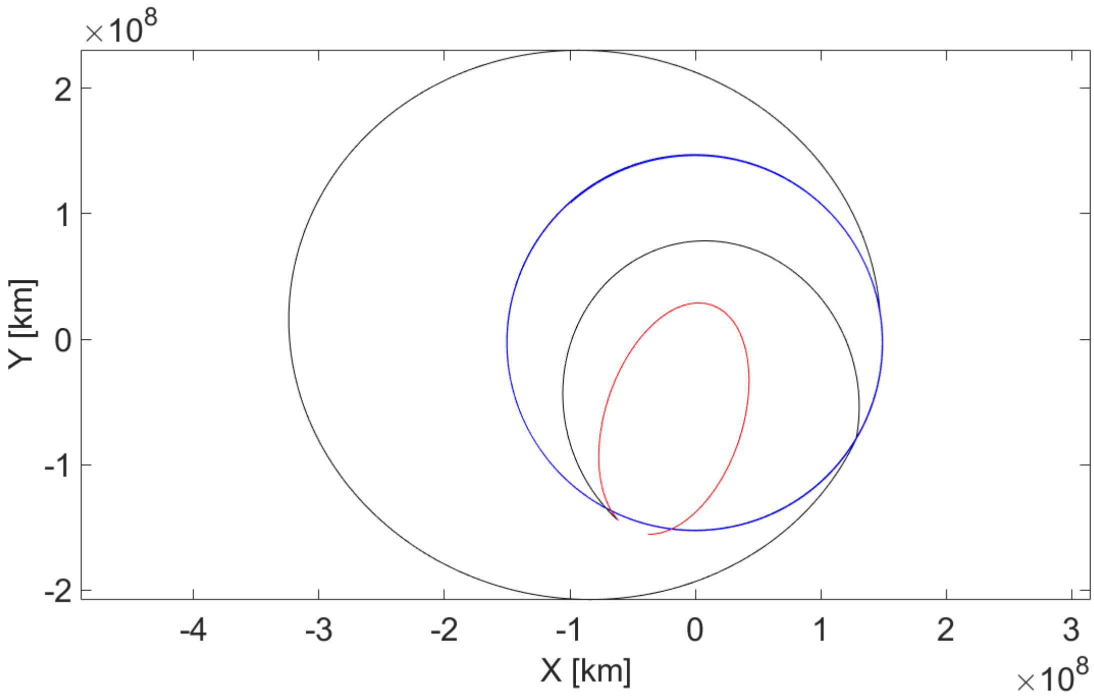

Figure C.62: 66391 (1999 KW_4)

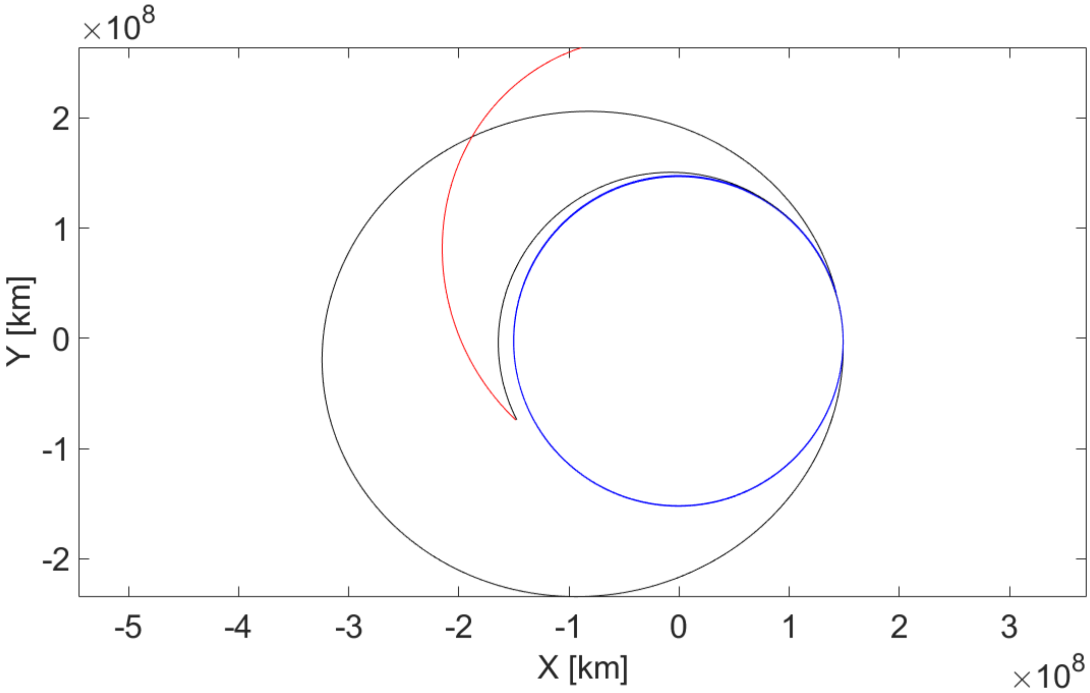

Figure C.63: 185851 (2000 DP_{107})

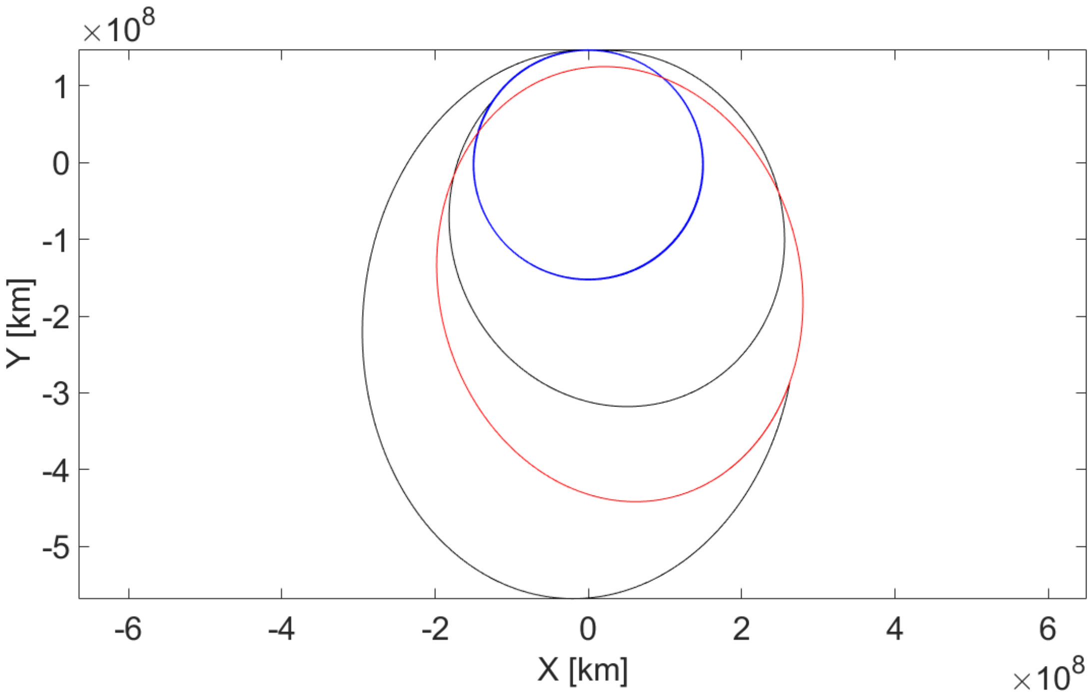

Figure C.64: 494658 (2000 UG_{11})

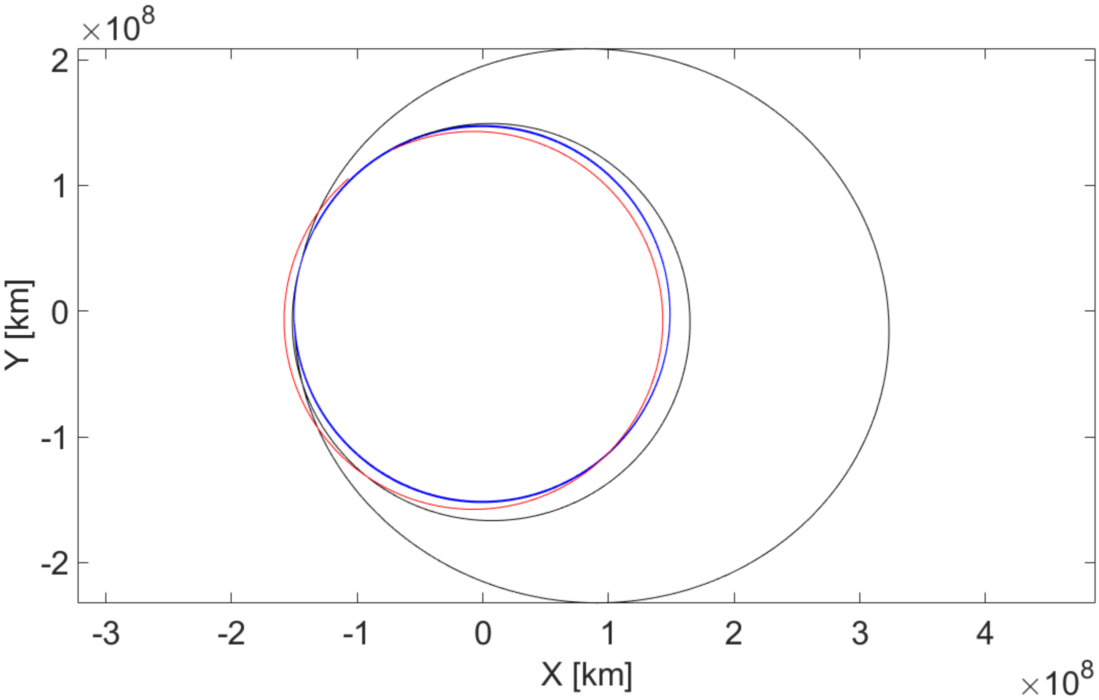

Figure C.65: — (2014 EK_{24})

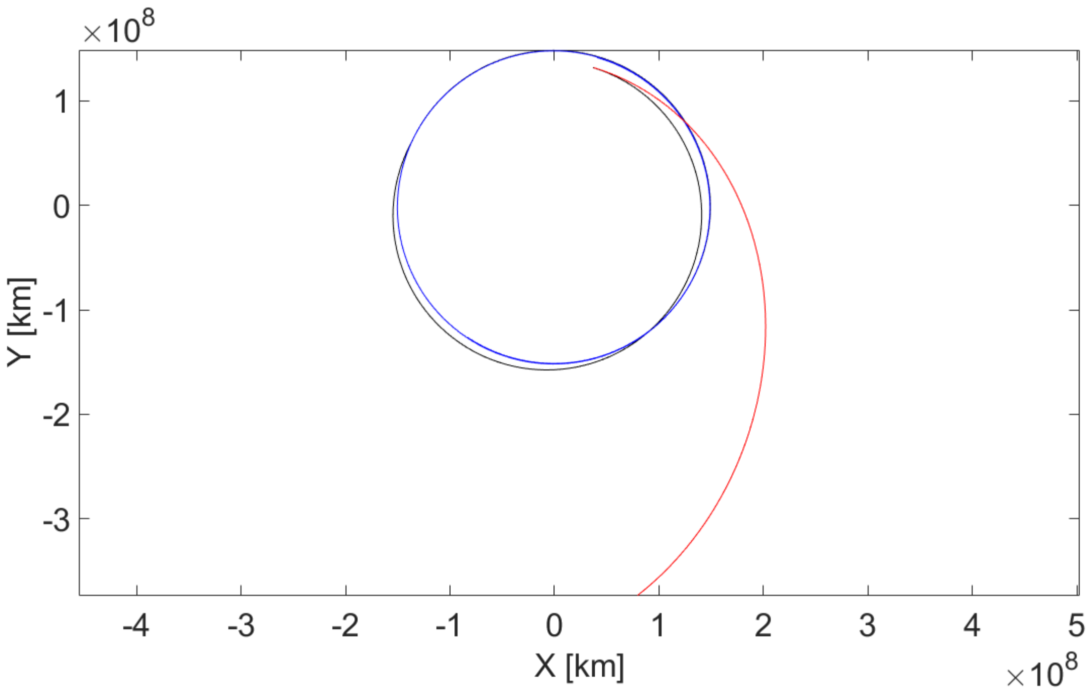

Figure C.66: — (2014 SC_{324})

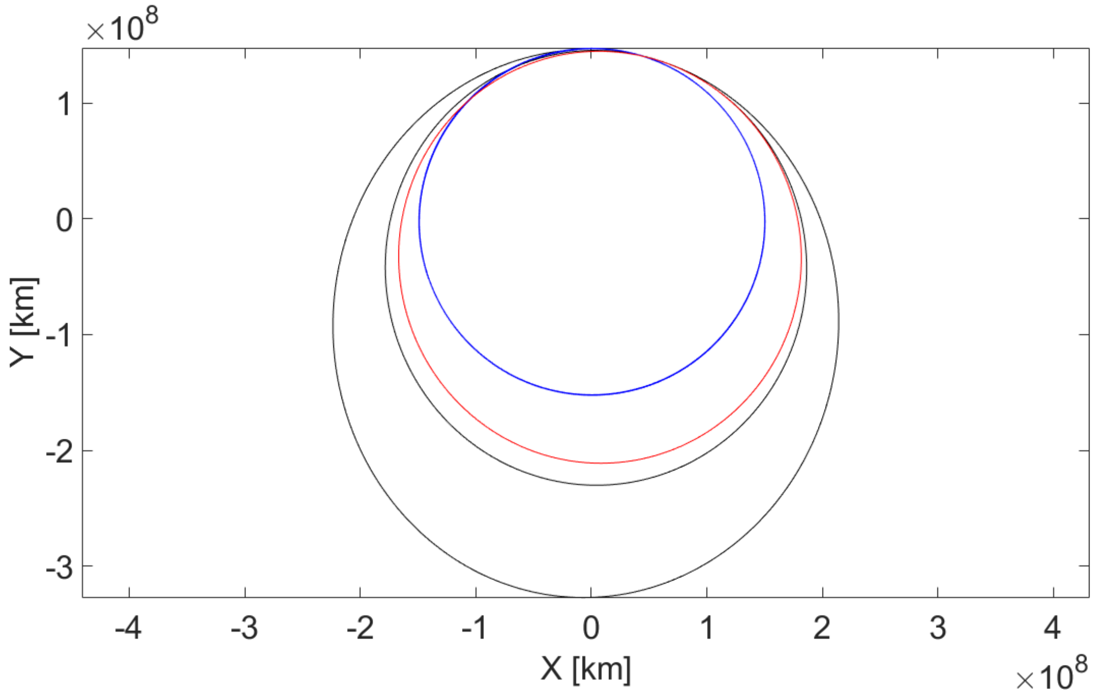

Figure C.67: 162173 Ryugu (1999 JU_3)

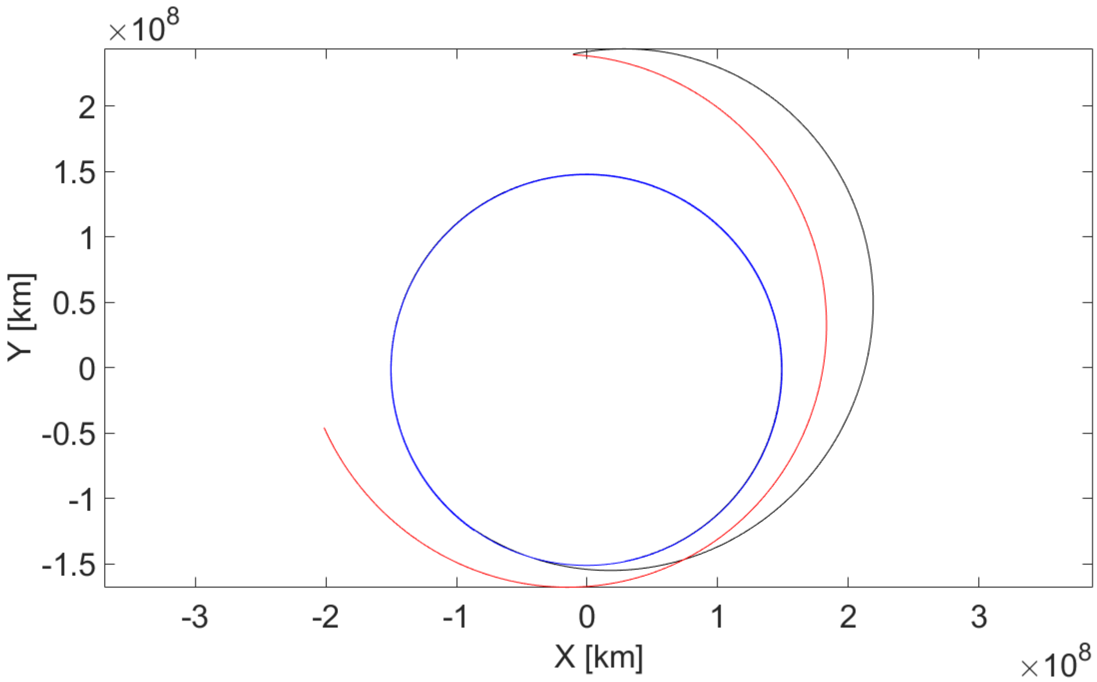

Figure C.68: 253062 (2002 TC_{70})

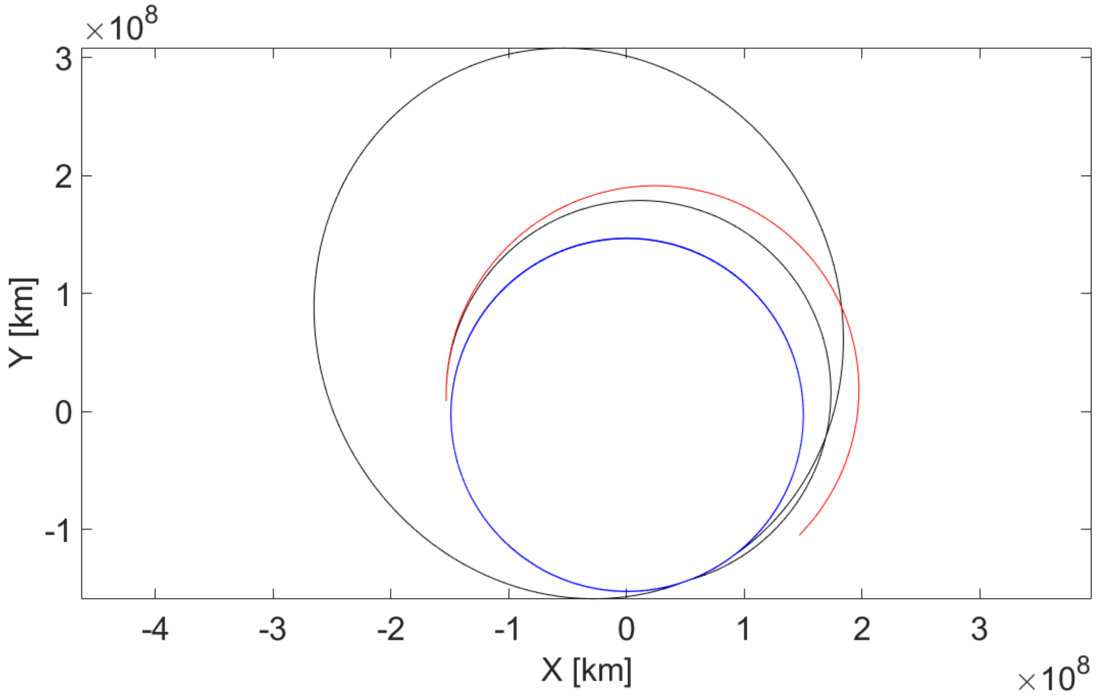

Figure C.69: — (2011 CG_2

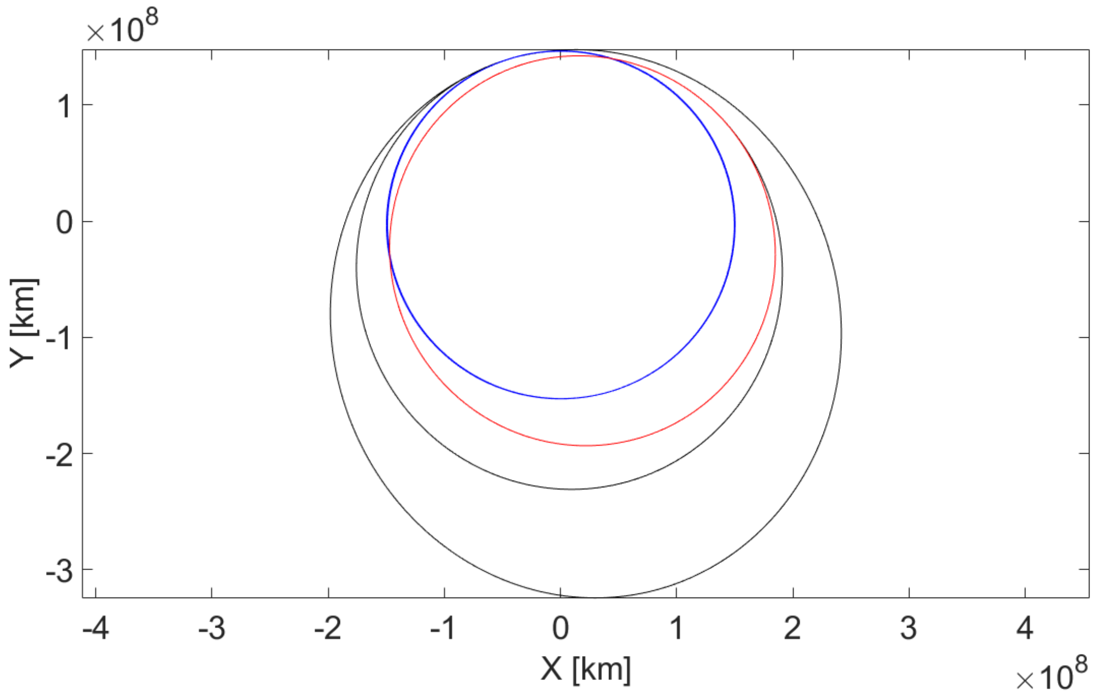

Figure C.70: — (2001 QC_{34})

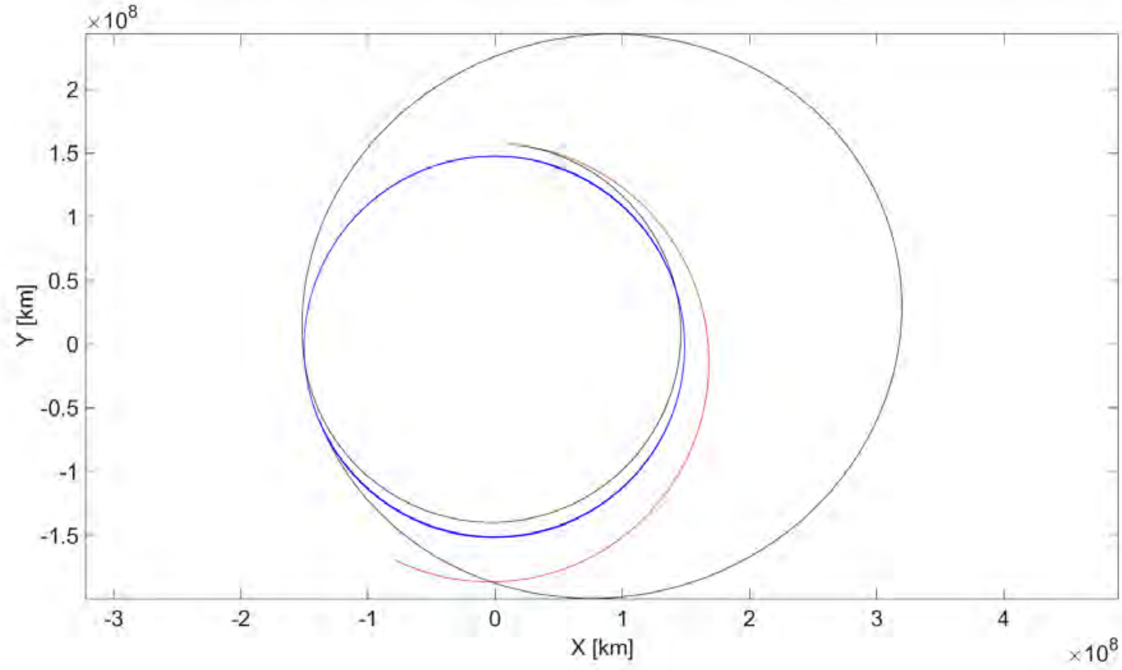

Figure C.71: — (2013 PA_7)

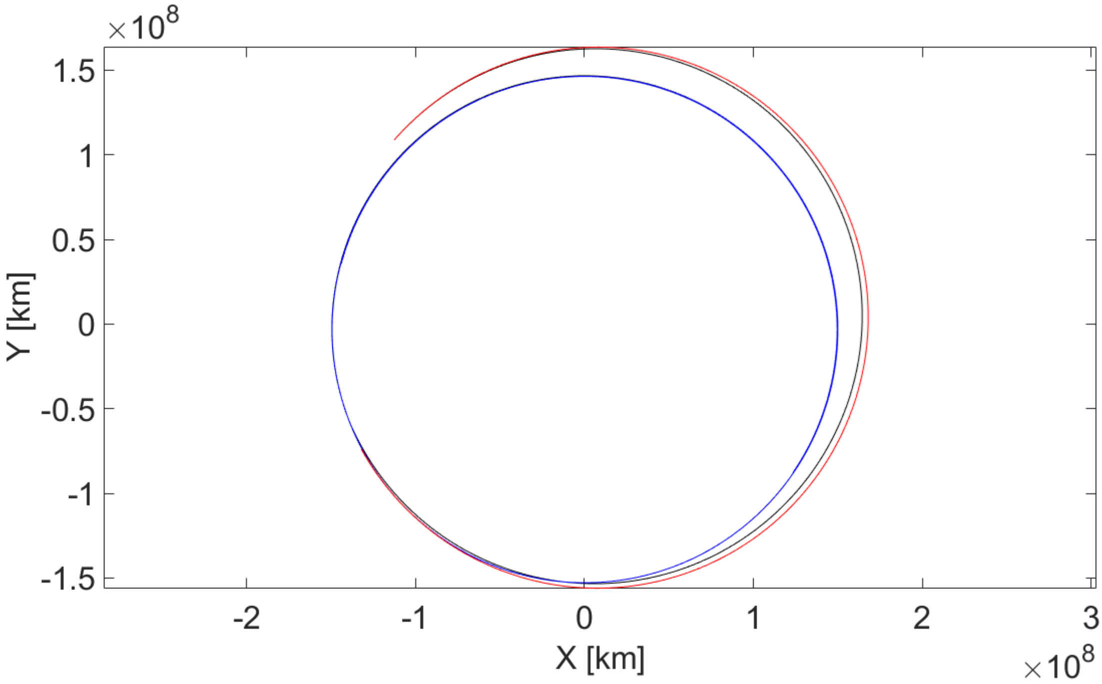

Figure C.72: — (2008 HU_4)

Bibliography

[1] J. Kargel, "Asteroids: Sources of precious metals," *Space Resources News*, vol. 12, no. 3, 1994.

[2] J. M. Diamond and D. Ordunio, *Guns, germs, and steel.* Books on Tape, 2011.

[3] R. F. Tylecote and R. Tylecote, *A history of metallurgy.* Institute of materials London, 1992.

[4] I. McNeil, *An encyclopedia of the history of technology.* Routledge, 2002.

[5] F. Habashi, "A short history of hydrometallurgy," *Hydrometallurgy*, vol. 79, no. 1, pp. 15–22, 2005.

[6] M. Kundak, L. Lazić, and J. Črnko, "Co 2 emissions in the steel industry.," *Metalurgija*, vol. 48, no. 3, 2009.

[7] I. T. A. U. D. of Commerce, "Global steel report," 2016.

[8] C. Stager, *Deep future: the next 100,000 years of life on earth.* Macmillan, 2011.

[9] B. B. Ciftci, "Global steel industry: outlook, challenges and opportunities," in *5th International Steel Industry & Sector Relation Conferences*, 2017.

[10] A. d. C. Filipe Silva, "Evaluating the financial health of the steel industry," 2015.

[11] A. H. Magnus Ericsson, "Trends in the mining and metals industry," 2012.

[12] G. James, "Metal industry indicators. indicator of domestic primary metals, steel, aluminum, and copper activity," 2016.

[13] J. S. Lewis, "Mining the sky: untold riches from the asteroids, comets, and planets," *Reading, Mass.: Addison-Wesley Pub. Co., c1996.*, 1996.

[14] COPUOS, "Resolution 71/90. international cooperation in the peaceful uses of outer space.," 2016.

[15] G. A. 21st session, "Res 2222 (xxi) - treaty on principles governing the activities of states in the exploration and use of outer space, including the moon and other celestial bodies," 1966.

[16] G. A. 34th session, "Res 34/68 - agreement governing the activities of states on the moon and other celestial bodies," 1966.

[17] G. A. 34th session, "Status of international agreements relating to activities in outer space as at 1 january 2017," 2017.

[18] L. I. Institute, "Chapter 513 - space resource commercial exploration and utilization," 2015.

[19] D. G. Andrews, K. Bonner, A. Butterworth, H. Calvert, B. Dagang, K. Dimond, L. Eckenroth, J. Erickson, B. Gilbertson, N. Gompertz, *et al.*, "Defining a successful commercial asteroid mining program," *Acta Astronautica*, vol. 108, pp. 106–118, 2015.

[20] J. B. Debi-Lee Wilkinson, Ueli Scheuermeier and D. Ellende, "Rig for mining asteroids," 2007.

[21] E. Jerby and V. Dikhtyar, "Drilling into hard non-conductive materials by localized microwave radiation," in *Advances in Microwave and Radio Frequency Processing*, pp. 687–694, Springer, 2006.

[22] K. Skonieczny, D. Wettergreen, and W. R. Whittaker, "Advantages of continuous excavation in lightweight planetary robotic operations," *The International Journal of Robotics Research*, vol. 35, no. 9, pp. 1121–1139, 2016.

[23] M. J. Sonter, "The technical and economic feasibility of mining the near-earth asteroids," *Acta Astronautica*, vol. 41, no. 4-10, pp. 637–647, 1997.

[24] S. D. Ross, "Near-earth asteroid mining," *Space*, 2001.

[25] J. P. Sanchez and C. R. McInnes, "Assessment on the feasibility of future shepherding of asteroid resources," *Acta Astronautica*, vol. 73, pp. 49–66, 2012.

[26] J. R. Brophy, L. Friedman, and F. Culick, "Asteroid retrieval feasibility," in *Aerospace Conference, 2012 IEEE*, pp. 1–16, IEEE, 2012.

[27] H. D. Curtis, *Orbital mechanics for engineering students.* Butterworth-Heinemann, 2013.

[28] D. J. Tholen and M. A. Barucci, "Asteroid taxonomy," in *Asteroids II*, pp. 298–315, 1989.

[29] S. J. Bus, "Compositional structure in the asteroid belt: Results of a spectroscopic survey," 1999.

[30] R. P. Binzel, A. S. Rivkin, J. S. Stuart, A. W. Harris, S. J. Bus, and T. H. Burbine, "Observed spectral properties of near-earth objects: results for population distribution, source regions, and space weathering processes," *Icarus*, vol. 170, no. 2, pp. 259–294, 2004.

[31] R. P. Binzel, A. W. Harris, S. J. Bus, and T. H. Burbine, "Spectral properties of near-earth objects: Palomar and irtf results for 48 objects including spacecraft targets (9969) braille and (10302) 1989 ml," *Icarus*, vol. 151, no. 2, pp. 139–149, 2001.

[32] M. J. Gaffey, "Spectral reflectance characteristics of the meteorite classes," *Journal of Geophysical Research*, vol. 81, no. 5, pp. 905–920, 1976.

[33] J. De León, J. Licandro, M. Serra-Ricart, N. Pinilla-Alonso, and H. Campins, "Observations, compositional, and physical characterization of near-earth and mars-crosser asteroids from a spectroscopic survey," *Astronomy & Astrophysics*, vol. 517, p. A23, 2010.

[34] P. Sukumaran, "Mining asteroid resources," *Geological Society of India*, vol. 88, no. 1, pp. 125–125, 2016.

[35] A. M. Ron, *El ojo desnudo.* Crítica, 2016.

[36] A. W. Harris, "On the revision of radiometric albedos and diameters of asteroids," *Icarus*, vol. 126, no. 2, pp. 450–454, 1997.

[37] J. L. Hilton, "Asteroid masses and densities," *Asteroids III*, vol. 1, pp. 103–112, 2002.

[38] D. A. Vallado, *Fundamentals of astrodynamics and applications*, vol. 12. Springer Science & Business Media, 2001.

[39] M. Mitchell, *An introduction to genetic algorithms.* MIT press, 1998.

[40] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: Nsga-ii," *IEEE transactions on evolutionary computation*, vol. 6, no. 2, pp. 182–197, 2002.

[41] A. Seshadri, "Nsga-ii: A multi-objective optimization algorithm," *MAT-Lab Central, Implementierung*, 2009.